



Scientific report

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Tuneable Lasers for Countermeasures

A Literature Survey

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# Tuneable Lasers for Countermeasures A Literature Survey

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Tuneable Lasers for Countermeasures - A Literature Surv	<i>r</i> ey		
Directed infrared countermeasures (DIRCM) against infra tuneable in band laser sources. When combining a laser of parametric oscillators it is possible to cover a large part of atmosphere. Also the 8-12 µm band may be accessible with This is an initiative to resume the development of lasers for countermeasures (DIRCM) applications at FOI. In this replay some examples of ongoing developments of DIRCM significantly discussed and briefly explained. Various pump-sources a survey of different IR-OPO techniques with results from conneeds are discussed and some suggestions for future would be supplied to the property of t	with wavelength conversion of the 2-5 µm wavelength trans with this or similar techniques. For countermeasures especiall fort a survey of the developm systems. Some methods for five then shortly discussed. The	devices such as optical mission window in the y for directed infrared ent of threats is given followed requency conversion are is is followed by a literature	
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Riktade IR motmedel (eng. DIRCM) mot IR-robotar kommuppnå om man använder en pumplaser och våglängdsko oscillatorer) för att uppnå avstämning i 2-5 µm men även inom dessa våglängdsområden för DIRCM har nu återup.  Denna rapport beskriver helt kort hotutvecklingen på sens	onvertering t e x med OPO (op 8-12 µm -fönstren i atmosfäre ptagits vid FOI. sorsidan varefter en översikt ö	otiska parametriska en. Utveckling av laserkällor over pågående internationell	
utveckling av DIRCM och därmed relaterade system ges. förklaras. Olika pumpkällor diskuteras helt kort varefter rapkonvertering till mellan-IR området.			
Slutligen ges förslag på verksamhet samt en lista på någr	a relevanta forskningsproblen	n inom området.	
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# 1. Introduction and background

The development of intelligent IR seekers, which can distinguish targets from countermeasures such as flares, motivates the development of mid-IR countermeasures. The seekers utilise scanners, primarily sensitive in the range 2-5  $\mu$ m. Anti sensor lasers exhibit an apparent advantage over flashlamp jammers, both due to the directed energy and the in-band emission. Furthermore, they can be used in closed loop arrangements where the retroreflection is used for fine tracking. Directed infrared countermeasures (DIRCM) against infrared sensing missile seekers generally require wavelength tuneable in-band laser sources. When combining a laser with wavelength conversion devices such as optical parametric oscillators it is possible to cover a large part of the 2-5  $\mu$ m wavelength atmospheric transmission window. Also the 8-12  $\mu$ m transmission window can be accessible with this technique.

This is an initiative to resume the development of lasers for countermeasures especially for directed infrared countermeasures (DIRCM) applications. The development of such lasers at FOI was initiated by Dr Göran Hansson, resulting in several publications on tuneable OPOs based on various pump-sources, as well as a Ph.D. thesis on the subject [1]. The nonlinear crystals LiNbO $_3$  and RTA were used in the OPO configurations. The crystals were periodically poled, making it possible to obtain high output power by quasi-phasematching (QPM). The OPOs were pumped with different lasers such as Nd:YAG at 1.064  $\mu$ m and Tm,Ho:YLF lasers at  $\sim$ 2  $\mu$ m.

In this report a survey of the optronic threats in defense systems is given. Some examples of on-going development of DIRCM systems are discussed. Methods for frequency conversion are reviewed and briefly explained. In the same section a short introduction to frequency conversion and wavelength tuning with OPO techniques is also presented followed by a survey of some nonlinear crystals. The choice of crystals for wavelength conversion is crucial. Various pump-sources are discussed. This is followed by a literature survey of different IR-OPO techniques with results from conversion to mid-IR wavelengths. Modelling of such systems and UV-lasers are also briefly introduced. Using Pump-laser sources around 1 µm the technique of wavelength up-conversion into the UV is often similar to the down-conversion to IR. Finally current and future needs are discussed and some suggestions for future work on this subject are given.

# 2. The optronic threat - a brief overview

With the optic or optronic threat we here mean all optical sensors from the human eye to advanced IR-seeker equipment and missile seekers. Anti sensor lasers operating at appropriate wavelengths can be used as countermeasures against these. A rough classification and corresponding wavelength-range can be made according to table 2.1.

Type of system	Type of sensor	Wavelength range	Note
Sight/reconnaissance	TV CCD, image intensifier	0.4-1.1 (1.5) μm	Possibly UV
			sensors under
			development.
"	Imaging IR incl. IRST	1.5-5, 3-5, 8-12 μm	Multi-spectral
		·	sensors under
			development
Missile systems	Reticle seeker	1.6-2.3; 2.7-3.6; 3.7-4.8 μm	
"	Imaging	0.4-1.1, 3-5; 8-12 μm	Multi-spectral
		·	sensors under
			development
"	Beam rider	0.8-1, 1.06, 10 μm	
"	Semi active laser	1.06 μm	

To counteract optronic sensors it is desirable to cover the entire optical range with only one single source. The approximate requirements on the laser for different countermeasures are summarized in table 2.2.

Table 2.2. Approximate requirements on the laser for countermeasures against optical threats.

Type of system	Type of sensor	Requirements on the laser	Note
		(figurative) 0.1-100 W CW or high prf	
Sight/reconnaissance	<b>Sight/reconnaissance</b> TV CCD, image intensifier		kJ/pulse for
		jamming	frosting entrance
		> 1 J/pulse damaging	optics
"	Imaging IR incl. IRST	1 W-1 kW CW / high prf	kJ/pulse for
		jamming-damaging	frosting entrance
		> 1 J/pulse for sensor	optics
		destruction	
Missile system	Reticle seeker	10-20 W CW / high prf	
		> 0.1 J/pulse for sensor	
		destruction	
"	Imaging	1-50 W CW/high prf	
"	Beam rider	Saturation, see TV/IR	
		Deception, low power	
"	Semi active laser	Saturation, see TV/IR	
		Deception, low power	

The capability of the ultimate antisensor laser technology should be:

- Potential emission between 0.4-12 μm, tuneable or multi-wavelength
- Possibility to switch between emission modes, from high prf or CW to single high energy pulse.
- Compact and robust for fitting into different platforms.

The physical reality will restrict the use of a single (or a few) laser sources for all these requirements. Here it will be focused on optical sensors in weapon systems operating with IR sensitive sensors.

# 2.1. Missile threat, specially anti-aircraft and attacking missiles

The IR-missile threat are usually denoted "the 90% threat" since 90% of all aircraft losses in battle over the past 25 years were caused by IR-missiles. Handheld SAM<sup>#</sup> IR-missile systems are available all over the world at as low cost as 5000 US \$. Over 500 000 SAM-missiles have been manufactured. In operations with landing and take off are particularly critical moments since also expensive and otherwise "well protected" platforms are vulnerable to fire. The situation occurs often at international operations in remote areas of the world. The IR-missile threat has evolved from seekers with AM to FM to pulse position reticles\*. Imaging seekers are currently under development. There is a strong demand on new countermeasures (read lasers) to handle all future missile threats.

IR-seekers can be classified as "spin scan - con scan" (e.g. Sidewinder, red eye, SA 7/9, SA 13 etc.) which were developed and put in operation between 1960 and 1990. These were followed by "pulse position seekers" (rosette, quadrant) with Stinger (SA-18) and Chapparal (AA-10,AA-11) as examples. Now imaging IR-seekers are under development (IRIS-T, MISTRAL). The following countermeasures are considered to be the most efficient ones:

Table 2.3. Efficiency of countermeasures against seekers

Type of seeker	Deception	Dazzling	Damaging
Spin scan - con scan	X	X	(x)
Pulse position	(x)	X	X
Imaging	(-)	X	X

X: Very efficient; x: efficient; (x): not efficient; (-): not possible.

.

<sup>\*</sup> SAM: Surface-to-Air Missile.

<sup>\*</sup> For a general description of reticles and IR Missiles see for example: The Infrared and Electro-Optical Systems Handbook, Vol 7, Ch. 3, SPIE Optical Engineering Press, 1993.

We see here that a combined dazzling and damaging system is the optimal choice to handle all kinds of threat seekers. One can in the near future have dazzling and jamming systems on fast aircraft (operational before 2010). Compact laser systems with destroying effects (requires 50-100 mJ/pulse) are not expected to be operative until 2010-2020.

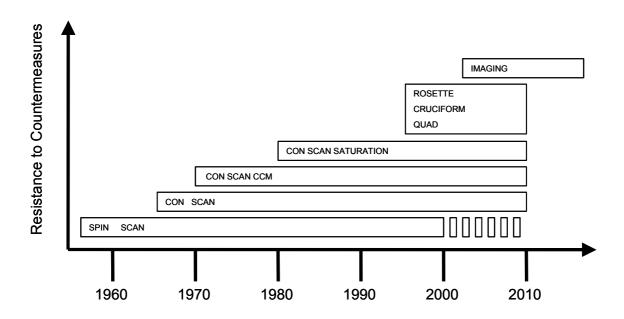


Figure 2.1. Missile threat against air targets, From Nortrop Grumman presentation.

# 3. Examples of on-going development of DIRCM systems

# 3.1. Background

Missiles can be jammed at long ranges (5 km or more) with modulation jamming from a laser or alternatively a flash-lamp. The flash lamp systems are operational today but the equipment is bulky and has a limited ability against modern missiles. The leading counter actions are "smart jamming", "dazzling" (saturation of detector signal, influence on automatic gain control, AGC) and finally damaging of the detector. Another important ability of the laser system is that they can be used in a <u>closed loop</u> whereby the retroreflection from the seeker can be used for fine tracking, as well as automatic classification of scanning sensors to allow optimal jamming. The so far developed systems have open loops but closed loop systems are under development. The systems in operation today (1st generation) are furthermore only using jamming. Systems with damaging effects can be expected after 2010. What primarily is limiting damaging systems is compact laser technology with high pulse energy (100 mJ during a relatively short pulse, at the order of microseconds or shorter). The wavelength must be suited to reach into the optics of the seeker to destroy the detector element(s).

Systems for protection of helicopters and transport aircrafts are in production. Tests on tactical aircrafts are planed within the next few years. The technique for fast aircrafts (small lasers and tracking heads) has evolved and should be operational round 2005-2010. Upgrading to systems with damaging effects, especially for imaging seekers means primarily a change of laser and this can be expected after 2010.

Much of the DIRCM technology relevant for aircrafts/helicopters can be transferred to the protection of vehicles and ships. To keep the costs down, concepts in terms of modules are appropriate.

There are now two competing systems on the market, Nortrup Grummans Nemesis (flashlamp/UV-warner) and the upgraded laser version Wanda (laser, 2-colour UV-warner). The latter can also be incorporated into tactical aircraft). Lockheed Sanders have developed ATIRCM (laser+ flashlamp/UV warner) and its upgraded version (TADIRCM containing the laser Agile Eye plus a 2-colour IR warner). Both systems have been tested with success with "live fire" in a cable-car in White Sands. Both systems work with open loops, i.e. without feedback.

# The Threat to Armored Vehicle Survivability

- Tank Cannon
- Anti-Tank Guided Missiles
- Rocket Propelled Grenades
- Smart Mortars

- Smart Munitions
  - Aircraft Delivered
  - Cannon Delivered
  - Rocket Delivered









**Figure 3.1.** The threat against tanks is versatile both regarding weapon types and demands on multi-spectral coverage (laser, IR, EO, acoustic and mm-waves). Picture from Northrop.

# 3.2. Vehicle based systems

Sanders develops an integrated HA system (Hit Avoidance) for tanks for the US Army's TARDEC (Tank Automative and Armaments Command Research, Development, Engineeering Center). The trend in USA is to make the tanks and other fighting vehicles lighter (a large initiative for the Army) and therefore one needs to improve the protection from IR and optronic threats. The threat is versatile, see Figure 3.1.

The number of different precision weapons against tanks will within the next ten years be almost 200. In Figure 3.2. some aspects on important issues together with the examined system are shown. Laser warners together with a connected decoy laser against range finders and semi-active laser weapons and a DIRCM system (build on Nemesis) using several laser wavelengths and a flash-lamp jammer. The system has also capacity to make use of retro reflection from sensors for reconnaissance, acquisition and tracking. No details on the laser systems have emerged.

The short burn time for many weapon threats, including those containing engines, motivates IR-based warners as a complement to or replacement of UV-warners.

The laser threat consists mainly of beam riding systems, semi-active systems and range finding. In the future optics detection and jamming laser systems will also add to the threats. The challenge for laser warners is a high angular resolution, in combination with classification of the threat based on the laser emission, which admits immediate counteraction (e.g. from DIRCM and other decoy lasers), which can be followed by other countermeasures (fog, manoeuvre etc.).



**Figure 3.2.** Example on development of vehicle based countermeasure system that utilises laser to mislead ATGM=anti tank guided missiles. Picture from Northrop.

There are also examples on development of vehicle based anti-sensor laser systems from other countries such as Russia. The company Granat Design Bureau – State Unitary Enterprise, was established in 1969 as a Laser Department of the Astrophysics Research and Production Association. Since 1992, Granat has operated as an independent state-owned enterprise involved in R&D and production of laser equipment.



Figure 3.3. An example on first-generation optical countermeasure laser system developed by Granat Design Bureau, Russia. <a href="http://www.milparade.com/2001/48/03">http://www.milparade.com/2001/48/03</a> 05.shtml.

The following information regarding the laser development at Granat (see figure 3.3):

- high-power pulsed solid-state lasers with low emission divergence and a pulse power of up to 2 kJ (in one laser module);
- systems with automatic aiming of high-power laser beam at reflecting (glittering) objects;
- high-power multicolor pulsed dye laser-pumped lasers with transformation of the emission wavelength;
- high-power repetitively-pulsed CO2 lasers, including those using wave front conjugation with a pulse energy of 1 kJ and more;
- compact power supplies for high-power lasers;
- automated computer systems for testing lasers and measuring laser emission parameters;
- special laser-optical systems, including high-precision laser retroreflectors for converting laser emission wave front;
- optronic countermeasures systems developed from the above types of lasers.

# 3.3. Ship based systems

In USA there are programmes on applications similar to DIRCM for ships. A programme called MATES includes laser in the IR-range for jamming optical sensors. The following excerpt from the US Navy budget gives an indication on ongoing laser jammer systems for ships:

http://www.dtic.mil/comptroller/fy2002budget/budget\_justification/pdfs/rdtande/vol4b\_dote.pdf

Table 3.1. Excerpt from the US Navy budget

	2000	2001	2002
Initiate	Infrared (IR) Search and Track (IRST)/Laser Detection and Ranging (LADAR) For Non Cooperative Target Recognition (NCTR) Ship based IRST Spectrally Balanced Decoy Materials against Advanced IR Surface-to-Air and Air-to-Air Missiles(SAMs – AAMs) Shipboard Laser Acquisition System for Self protection	3 <sup>rd</sup> Generation Airborne IRST For E-2C     Integrated Electro-Optic (EO)/IR ship self-protection	MSM Missile Warning System     EO/IR Laser Jammer for     TACAIR     Shipboard EO/IR Closed loop     Self Protection     EO/IR Self Protection for Small     Ground Vehicles     EUT++ (Higher Power/BW)     EO/IR Laser-based Jammer     Imaging IR Countermeasures     Long wave IR decoy Material     Electrical IR Decoy Launcer
Continue	Multicolor IR Threat Warning for tactical missile launch detection     Electrical IR Decoy Launcher     Hyperspectral/Imaging for Surveillance and Targeting (HI-STAR)	Ship based IRST     Shipboard Laser Acquisition     System for self-protection     Electrical IR Decoy Launcher	3 <sup>rd</sup> Generation Airborne IRST For E-2C     Ship based IRST     Electrical IR Decoy Launcher     Integrated (EO)/IR ship self-protection
Complete	E-2C Surveillance IRST Sensor     Shipboard IR decoy counter measures against modern Air –to–Surface Cruise Missile seekers	Spectrally Balanced Decoy     Materials against Advanced IR     SAMs – AAMs     Multicolor Threat Warning for     tactical missile launch detection     Hyperspectral/Imaging for     Surveillance and Targeting (HI-     STAR)	Shipboard Laser Acquisition System

System (IEWS/MATES) self protection programme for ships includes for the optical part:

- Complete integration and evaluation of the onboard/ offboard CM solution to laser- guided threats that will challenge Navy and Marine surface vessels operating in littoral areas.

- Incorporate a new mid- infrared solid state laser into the Multi- Band Anti- Ship Cruise Missile Defense Tactical Electronic Warfare System (MATES) testbed and investigate use of a compact IR countermeasures system for small shipboard platforms to provide an integrated multi- function, multi- band laser based countermeasures system for ship defense.

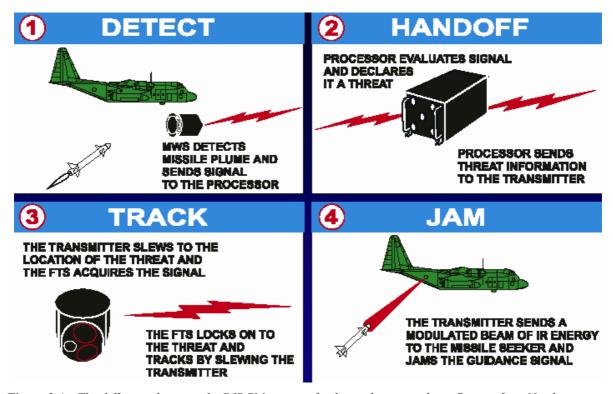
TRW develops a laser for MATES, a 20 W, prf 20 kHz, tuneable between 3.7 µm and 4.9 µm, which is about four times higher power than the previous record by a laser of this type in this spectral range.

(http://www.trw.com/productsandservices/main/0,2610.4 39 841 844 856^5^856^856,00.html).

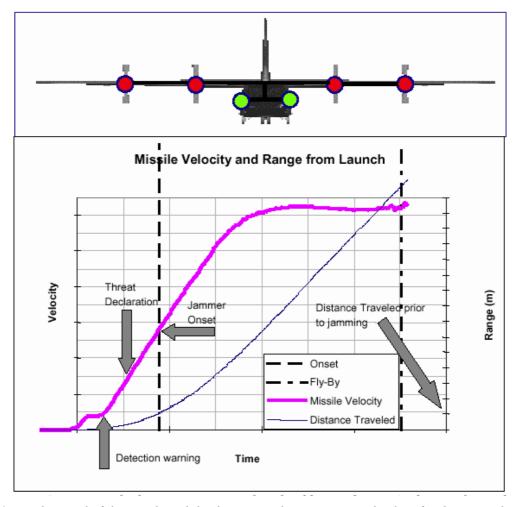
Similar programmes as those in USA are most likely existing in other countries.

# 3.4. Aircraft based system.

The development of laser based jamming systems of DIRCM type for flying platforms is ongoing in many countries e.g., USA, Germany, France, Italy, Israel, South Africa and Russia. The DIRCM-systems have been tested in a number of trials against missiles that operate both in band I and band IV (at 2 and 4  $\mu$ m, respectively, see section 4 for details) at ranges between 1 and 6 km. The systems have automatically detected the threats, handed over to the tracking unit, which tracks the missile and initiates the jamming code. The tracking accuracy can be on the order of 200  $\mu$ rad. Missile warners are based on IR or UV detection. Figure 3.4 and 3.5 show the process including the time .



*Figure 3.4.* The different phases in the DIRCM system of today with an open loop. Picture from Northrop Grumman.



**Figure 3.5.** The speed of the missile and the distance to the target. Typical values for the timescale are 0.5-1 second per scale mark and 100-200 meter per scale mark in range. Jamming takes place within one second from the threat declaration from the warner. This means that the seeker can be jammed before the missile has obtained a stable tracking. Picture from Northrop Grumman.

One of the most serious problems is to get good laser sources that cover all the wavelengths of the threat. Below we will comment on the development of two systems that have been described in open press.

#### ATIRCM/CMWS (BAE Sanders)

This is now a service programme where the army has the hole system including the combined flashlamp/laser jammer while the air force and the navy have the remaining parts (warners/torches). Figure 3.6 shows an overview of the programme.

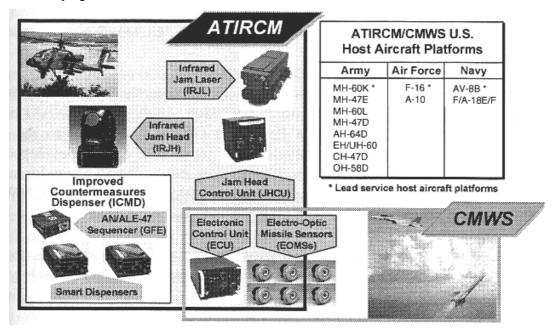
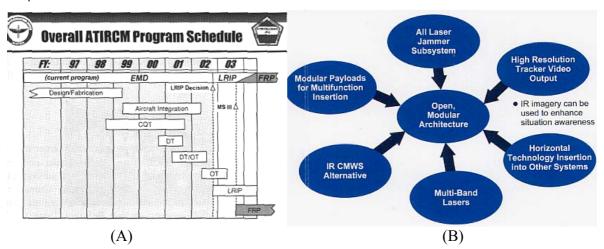


Figure 3.6. The ATIRCM/CMWS programme.

ATIRCM (Advanced Threat Infrared Countermeasures) includes a flash lamp and a laser jammer plus torches. In the future Lockheed Sanders plans to only use laser since it will yield a considerably more compact design (see comments about Lockheed Sanders under the exhibition comments). They utilise a UV-based warner and build the system on an open architecture that allows for future modifications (Figure 3.7.). One of the purposes with this system is to allow Apache and similar systems to make deep mission strikes without losses. According to the schedule a low rate initial production should start at the end of 2002 with a full rate production in 2003. The laser in the first version of ATIRCM is probably based on a frequency doubled  $CO_2$  laser with a wavelength of 4.6  $\mu$ m.



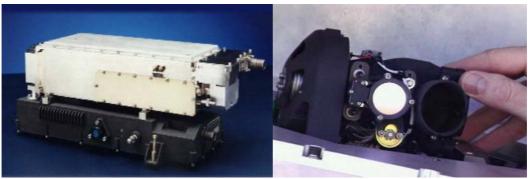
**Figure 3.7.** (A) Schedule for ATIRCM/CWES, key: CQT = Contractor Qualification Testing, OT= Operational Testing, LRIP Low rate Initial Production, FRP= Full Rate Production. (B) An open architecture allows for upgrades.

# TADIRCM (BAE Sanders)

TADIRCM (Tactical Aircraft Directional Infrared Countermeasures) is a further development of the ATIRCM intended for fast airplanes (Figure 3.8.). It contains the following components:

- A multiband laser (band I, II och IV; see section 4 for details))
- Fibercoupled laser for the scanner head.
- A very small scannerhead





**Figure 3.8.** Above: The complete TADIRCM system. Lower left: comparison of the size of TADIRCM and ATIRCM. At the centre the multi band IR laser and the tracker head to the right.

Lockheed has developed a new laser in the 2 -  $5~\mu m$  range (no technical details released) and a micro-optic head (Agile Eye) to fit to this. TADIRCM still relies on ATIRCM processor etc. and it is still an open loop (i.e. the retroreflex feedback is not being used). The missile warner consists of a two-colour sensor. During the fall 1999 a number of live fire tests took place with the equipment in the cable car in White Sands. Surface-to-air missiles were fired at 3-4.7 km distance and attacking missiles from 7 km. According to Lockheed the missiles were jammed and successfully defeated in all cases. The TADIRCM was recently (5 november 2001), as the first DIRCM system, tested live mounted in a fast flying drone.

They also intend to develop and implement a semiconductor laser with fibercoupling to the TADIRCM head to further reduce the size. A present, a risk reduction programme is going on for TADIRCM where the two-colour IR warner, the laser and the scanner head are further developed. The jam codes are also developed further.

# NEMESIS (Northrop Grumman m fl)

Nemesis (AN/AAQ-24(V) / ARI 18246) is the only DIRCM in full scale production (Figure 3.9). Nemesis was started as a UK/US programme in 1989. It contains a UV warner + flashlamp jammer. In the most upgraded version a laser replaces the lamp. It is today produced for both helicopters and larger airplanes. A considerable amount of simulations (> 150.000) together with totally autonomous live fire tests with the system placed in a cable car have been performed. Figure 3.10 shows a summary of these tests. In more than 90% of the tests sufficient miss distance for 100 % platform survivability was achieved The equipment was 100% reliable during the tests. The missile fire took place from the ground at distances of ca 1-6 km. At the shortest distance the time to hit from fire is only a few seconds so the system must immediately detect the threat and within 1 second direct the beam to the target and commence jamming. Multiple treats with two missiles fired within 3 seconds were also tested but no information on the results were given.



Figure 3.9. The Nemesis-system, Norhrop Grumman.



Figure 3.10. Live fire tests with the Nemesis-system in a cable car.

The missile warner is now upgraded from UV to two-colour IR. The intention is, as previously pointed out, to be able to detect out-burned missiles and missiles with low IR signature. The two-colour technique is based on the quotient between the red and the blue spikes within each part in the 3-5  $\mu$ m ranges with low atmospheric transmission between. Some problems remains with false alarms (close to refineries etc.) with two-colour warners.

The motive for upgrading is not the warner in it-self. A completely new compact laser based system could be operative in tactical aircrafts. Figure 3.1 shows WANDA. Northrop hopes to be able to fly WANDA in a pod with one head looking forward and one backwards in order to evaluate its performance in a fast tactical aircraft. Stabilisation of the beam is probably one of the difficult problems, especially under heavy g-forces.



**Figure3.11.** To the left: WANDA. To the right: The parts that upgrade Nemesis to WANDA, a new laser, a new tracking head and the two colour IR missile warning sensor.

By comparing with the pen in Figure 3.13 one really gets an impression on how compact the transmitter and the laser are. Note the size of the laser. It consists of a Nd:YAG laser (Viper  $^{TM}$ ) pumping a periodically poled LiNbO<sub>3</sub> (PPLN) crystal emitting between 2.6-4  $\mu m$  with an average power of 3-4 W. The frequency conversion can be obtained in three wavelengths simultaneously and thereby allow for simultaneous jamming in infrared band I, II and IV (see section 4 for detailed definition of bands).

With different PPLN configurations it is possible to generate radiation in two or three of the infrared regions. The challenge for DIRCM on fast aircrafts is the development of compact units that fits onto the small platforms, see Figure 3.12

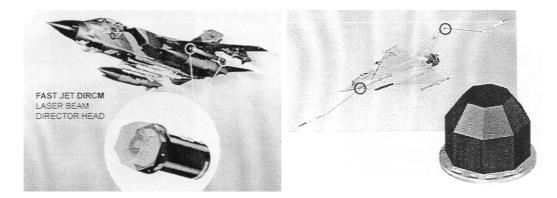


Figure 3.12 Concepts for design and placement of small DIRCM heads on fast airplanes. Source: BAE systems.



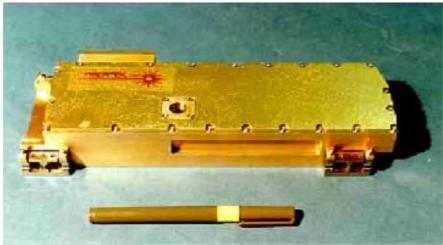


Figure 3.13. The laser ViperTM. Note the small jamming head and that the laser is tuneable between 2.4-4 μm.

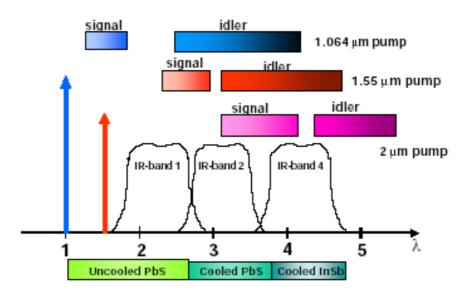
The laser is probably Q-switched with 10-20 kHz prf that can be modulated to realise appropriate jam codes. Note that the rotation of the missile needs to be accounted for when a proper jam code is chosen. Nemesis is working with an open loop so it is necessary to choose a generic jam code that fits as many missiles as possible (the jam codes might be produced in a sequence with some kind of priority).

In the following section it will be focused on laser technology development in terms of tuneable mid-IR lasers.

# 4. Frequency conversion to the infrared region

Tuneability of the wavelength of a laser can be accomplished by a number of means. Common tuneable lasers are dye lasers, tuneable excimer lasers, tuneable solid-state and semiconductor lasers and free electron lasers. For wide tuneability the most common way is to utilise the second order nonlinearity of a crystalline material in order to accomplish optical parametric generation (OPG). In this process one photon is divided into two photons with lower energies, i.e. longer wavelengths. Furthermore, Raman shifters can be used to convert to longer wavelengths although this is not a tuneable process. Conversion to shorter wavelengths like doubling and tripling of the frequency can be accomplished with so called second and third order harmonics in similar optically nonlinear crystals.

One objective with the previous research at FOI was to obtain a laser that emits tuneable light with wavelengths primarily between 2 and 5  $\mu$ m. Several different ways to reach this region were suggested see e.g. [1]. One way was to use the up-converted harmonics from a CO<sub>2</sub> laser, generated by propagation through nonlinear crystals. The tuning range is then limited by the tuneability of the pump-source. Dye lasers and solid state diode pumped lasers are common tuneable lasers for generation of light in the visible and the NIR. This concept was extended to work in the near infrared region. The most exploited and most powerful concept with a wide tuning range today is to use some kind of solid state optical parametric oscillator (OPO) pumped at either at 1064 nm with a Nd:YAG laser, or pumped at 1.5 or  $2\mu$ m with Erbium or Holmium based amplifying gain media, respectively. OPG to generate radiation in various IR regions from certain pump wavelengths are summarized in Figure 4.1. The concept of OPO and the underlying theory will briefly be discussed in this chapter.



**Figure 4.1.** OPO frequency conversion with different pump-sources and the different operating ranges of missile threats.

#### 4.1. Optical parametric generation

With nonlinear materials it is possible to generate light with tuneable output. The nonlinearity enters due to the nonlinear polarisation of the material. For such media the polarisation can be written:

$$\mathbf{P}(t) = \boldsymbol{\varepsilon}_0 \left[ \boldsymbol{\chi}^{(1)} \mathbf{E}(t) + \boldsymbol{\chi}^{(2)} \mathbf{E}^2(t) + \dots \right] = \mathbf{P}^L + \mathbf{P}^{NL}, \tag{1}$$

where  $\chi^{(1)}$  is the linear susceptibility and  $\chi^{(2)}$  is the second order nonlinear susceptibility. The second order nonlinearity is used for second harmonic generation (SHG) and optical parametric generation (OPG). From eq. 1 one can see that the nonlinear polarisation  $\boldsymbol{P}^{NL}$  is dependent on the square of the electric field, i.e., the peak irradiance of the radiation (intensity). The second order nonlinear susceptibility is generally described by a 3<sup>rd</sup>

rank tensor to take into account the relations between the polarization of the interacting fields and the anisotropic medium. Thus three different photons are involved in these processes. In SHG two photons of the pump field generate a third, whereas for OPG one pump photon field at one frequency photon generates two new photons at different characteristic frequencies. The generated wavelengths and conversion efficiencies are strongly related to phase-matching conditions and hereby the optical anisotropy of the crystal. Some further details are discussed below.

To satisfy the conservation of energy the sum of the generated photons energy must equal the energy of the pump photon. For an OPO process here frequency 1 is used to generate two fields 2 and 3 (Figure 4.2.). For the upconversion process this would be the sum frequency generation of field 2 and 3 to generate field 1. The energy of a photon is  $hv=hc/\lambda$  where h is Planck's constant, v is the frequency of the photon, c is the speed of light and  $\lambda$  is the wavelength. The conservation of energy can then be written

$$v_1 = v_2 + v_3. (2)$$

An additional condition is that the momentum must be conserved:

$$\mathbf{k}_1 = \mathbf{k}_2 + \mathbf{k}_3,\tag{3}$$

where  $\mathbf{k_i}$  is the wave vector associated with frequency  $v_i$ . This is the basis for "phase-matching conditions". One of the most interesting and illustrative cases is when the interacting waves are collinear, and the vector relation reduces to an algebraic relation

$$n_1 V = n_2 V_2 + n_3 V_3 \tag{4}$$

since  $k_i = 2\pi n_i/\lambda_i$  where  $n_i$  is the refractive index at the wavelength  $\lambda_i$ . In an OPG process the different photons are denoted pump-, signal- and idler-photons, where the pump is the input while the shortest output wavelength is denoted signal and the idler is the longer of the generated ones.

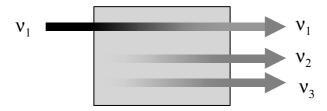


Figure 4.2. Optical parametric generation with second order nonlinear material.

Phasematching is essential to obtain a significant output from a nonlinear crystal. Unless the phasematching condition,  $\Delta \mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2 - \mathbf{k}_3 = 0$ , is met the interacting waves will after a certain distance start interfere destructively to cancel out the generated field. This characteristic length is called the coherence length,  $L_c$ ,

There are several ways to tune the wavelength. The main idea is to adjust the refractive index to phasematch different wavelengths so that eq. 3 is satisfied. The usual way to get phasematching is called angular phasematching and uses the birefringence of the crystal by rotating it. Since the refractive index is dependent on the direction of the electric field in the crystal different wavelengths will be generated depending on the angle of the crystal. The nonlinear interactions can be classified as Type I and Type II interactions. If the signal and idler have the same polarisation the interaction is referred to as Type I interaction, whereas it is referred to as a Type II interaction if the signal and idler have different polarisations. In Figure 4.3-4.5 the phasematching angles and corresponding output wavelengths have been calculated for some nonlinear materials and specific pump

wavelengths. A brief discussion regarding different nonlinear materials will be given in a following section. Note the degeneracy point in the phasematching curves where the two output wavelengths, the signal and idler, are identical and twice the pump wavelength.

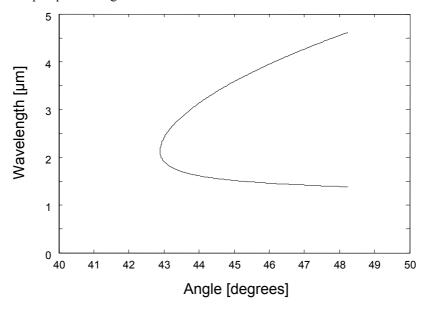
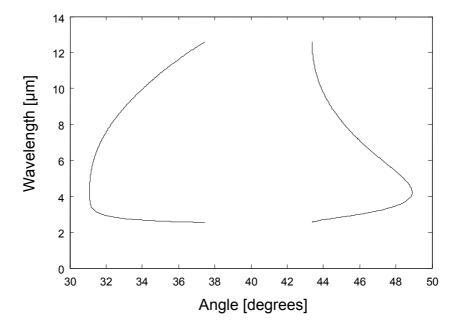
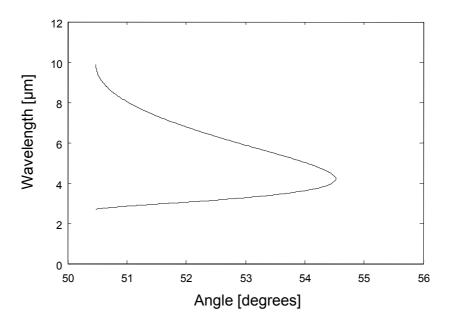


Figure 4.3. Phasematching curve for LiNbO<sub>3</sub> for a 1.064 μm pump-wavelength-



**Figure 4.4.** Phasematching curve for  $AgGaS_2$  to the left and  $AgGaSe_2$  to the right. Both with 2.10  $\mu$ m pumpwavelength.



*Figure 4.5.* Phasematching curve for ZnGeP<sub>2</sub> with 2.10 μm pump-wavelength.

A disadvantage of angular phasematching with birefringent crystals is that the beams with different polarisation are not collinear in the crystal and thus the birefringence leads to walkoff. Therefore after a certain distance,  $L_a$ , called the aperture distance, the ordinary and extraordinary beams have separated completely and do not interact anymore. This effect limits the length of the crystal that can be utilised. Pairs of crystals can then be used to compensate for the walk off by mounting them so that the walk off is reversed.

Quasi-phasematching (QPM) may also be used when one desires to reduce the walk-off of the pump and signal (Figure 4.6.). It is not as efficient as phasematching originating from perfect orientation and polarization combinations at short interaction lengths, but may be advantageous if the walk-off in the material is substantial, which often is the case for critical phasematching in birefringent materials. Quasi-phasematching can occur by periodically modifying the crystal structure, usually by alternatively changing the polarization, to compensate for the phase-difference from the wave vector mismatch. The alternating polarization introduces a periodic variation of the sign of the material nonlinearity at a spatial period along the propagation direction corresponding to  $2mL_c$  of the process, where m is an odd positive integer giving the order of the QPM and  $L_c$  is the characteristic coherence length [2, 3]. QPM can be achieved by stacking wafers rotated 180° and fusion bonding them to form a solid bulk. A more modern method is to periodically pole a crystal with a pulsed high voltage in domains to get sign reversal of the nonlinearity [4]. The efficiencies for different domain periodicity are summarized in Figure 4.7.

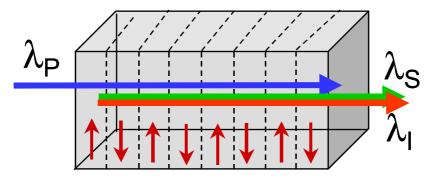
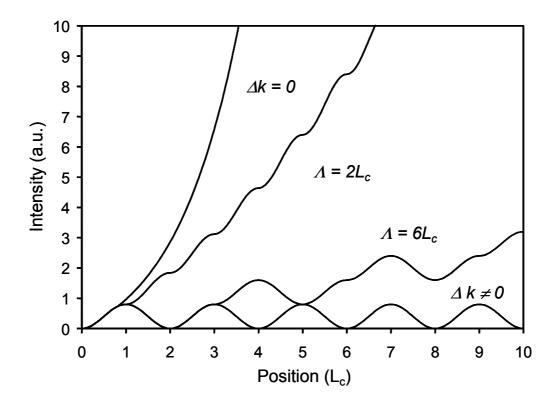


Figure 4.6. A periodically poled material for quasi-phasematching.



**Figure 4.7.** Quasi-phasematching with different periodicities. The increase in intensity with propagation for a generated wave in a quasi-phasmatched process is dependent on the order of the quasi-phasematching.

An additional way to change the refractive index is to heat or cool the crystal, since the refractive index and the period in the QPM crystal both depend on the temperature. This is a slow and difficult way to obtain phase-matching, since it is elaborate to fast and accurately tune the temperature of the crystal.

#### 4.2. OPO cavities

For OPG a cavity is not necessary, it can be accomplished with a single pass (single-pass optical parametric process) of a pump beam through the nonlinear material. The nonlinear material can also be put in an oscillator cavity whereby an OPO (optical parametric oscillator) is created. Due to the resonator cavity the output wavelength from an OPO can be made more efficient, with a narrower linewidth and better spatial profile than the output from a single pass OPG. A typical cavity design is depicted in Figure 4.8.

This technique is well established for tuning both visual and near infrared wavelengths. To exceed the threshold energy of the OPO a relatively high irradiance is required. This can be accomplished with short pulses and moderate power. To decrease the lasing threshold an intra-cavity configuration can be utilised or other tight focusing concepts may be used. For continuous waves a tight focusing in the nonlinear crystal is required to generate the parametric process. An OPO can be constructed both for continuous generation and for pulsed lasers. The simplest configuration relies on an external pump-source with a phase-matched nonlinear material in a cavity. The cavity can be single resonant (SRO), which means that only one of the generated wavelengths is resonant in the cavity, or double resonant (DRO), which means that the two generated wavelengths are resonant in the cavity. If also the pump is reflected inside the cavity it is called a double pass configuration, abbreviated DPSRO or DPDRO for the single and double resonant cases respectively.

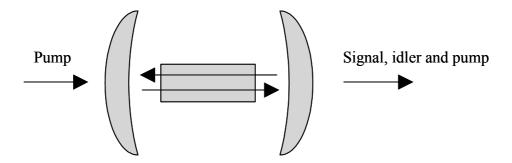


Figure 4.8. Basic OPO configuration with nonlinear phasematched crystal between two mirrors.

The simplest DRO consists of a nonlinear crystal in a two-mirror cavity. The mirrors should then have low reflectance at the pump frequency and high reflectance at both signal and idler frequencies. Both the signal and idler should thus be resonant with the cavity. The simplest SRO has two cavity mirrors with high reflectance at the signal frequency only and is resonant only at the signal frequency. SROs generally tend to be more stable against mode-hopping than DROs even though DROs often are more effective than SROs.

Another option is the so-called ring cavity. (see Figure 4.9) With this kind of configuration one avoids the risk of spatial hole burning.

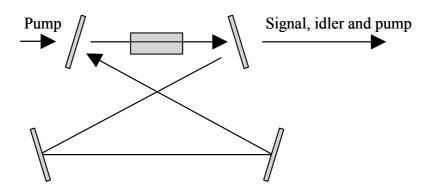
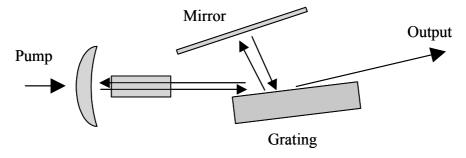


Figure 4.9. OPO constructed with a ring cavity



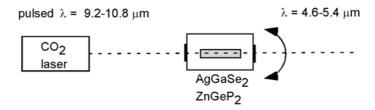
*Figure 4.10.* Grazing incidence configuration of an OPO with the nonlinear phase-matched crystal between two mirrors. With a grating inside the cavity a narrow bandwidth is produced in the oscillator.

To make an output with a narrower line-width a grating can be placed inside the cavity [5] (see Figure 4.10). The cavity must be adjusted together with the phase-matching angle, i.e. the phasematched wavelength must be able to oscillate in the cavity. This can be accomplished by tilting the mirror in order to reflect the chosen wavelength back on to the grating.

For a good beam profile of the OPO radiation it is essential that the pump beam stimulate only low order modes of the OPO cavity. This can be accomplished by making sure that the pump beam in the nonlinear crystal is smaller than the lowest order of this cavity. Another trick to make the OPO emit low order modes is to seed it with a single mode laser beam. (Strictly speaking one then has an OPA (optical parametric amplifier) since the seed beam is amplified by the pump)

# 4.3. Frequency doubling of CO<sub>2</sub> lasers

Radio frequency (rf) excited CO<sub>2</sub> lasers have been developed and studied for different applications. These lasers have low weight and small volume, provide high average output power, closed cycle operation and simple and reliable operation. By using an intra-cavity modulator short pulses with relatively high energy can be generated at high pulse repetition frequency (Figure 4.11). The closed cycle operation favours the rf-excited in comparison to the electrically discharged CO<sub>2</sub> laser. The output from a CO<sub>2</sub> laser can be shifted into the mid-ir wavelength region by second harmonic generation (frequency-doubling, SHG) reaching the upper part of band IV. Grating tuning is used to alter the wavelength of the CO<sub>2</sub> pump laser by choosing different vibration transitions. Second harmonic generation of CO<sub>2</sub> laser radiation has been thoroughly studied in the literature. The most commonly used non-linear crystals are AgGaSe<sub>2</sub> and ZnGeP<sub>2</sub> [6-8]. Up to 35% conversion efficiency can be obtained using these crystals for SHG of CO<sub>2</sub>. A particular efficient energy conversion scheme is to use an intra-cavity set-up where the SHG crystal is placed within the oscillator [9, 10].



*Figure 4.11.* Second harmonic generation of CO<sub>2</sub> laser irradiation.

In Table 4.1. the technical specification of a commercial (DEOS Inc., USA) frequency doubled  $CO_2$  laser is depicted. The laser is tuneable in the 4.6 to 5.4  $\mu$ m wavelength region covering the upper part of band IV. Short pulses with high prf can be generated. The average power is considered as adequate for jamming of IR missile seekers at shorter range. The beam quality ( $M^2 < 1.3$ ) is considerably better than the values usually obtained using diode pumped solid-state laser OPO's. The latter commonly exhibit a  $M^2$  above 1.8.

<b>Table 4.1.</b> Technical specification of a commercial frequency doubled 0	CO <sub>2</sub> laser	
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Wavelength	Prf [kHz]	Pulse duration [ns]	Power [W]	$M^2$	Beam divergence
[µm]					
4.6-5.4	0-100	< 12	2 W @ 100 kHz	< 1.3	$3.0 \pm 1 \text{ mrad}$

Frequency doubling of  $CO_2$  is a feasible way to generate laser radiation in band IV for threats operating above  $\lambda$  = 4.6  $\mu$ m. In order to cover the complete band III and IV additional sources are required. Optical parametric oscillators operating in the upper part of band IV are not currently commercially available. The  $CO_2$  laser can also be used without the SHG step in order to jam thermal imagery and thermal sights. Another interesting approach of SHG of  $CO_2$  is to develop a low pulse repetition rate laser with high pulse energy for sensor damage applications. One critical issue is the damage threshold and the size of the employed SHG crystal. Roughly, pulse energies of the order of 100 mJ is required to inflict damage in e.g. a thermal missile seeker at moderate

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<sup>\*</sup> http://www.deoslaser.com/

range. Frequency doubled CO<sub>2</sub> lasers with high single-pulse energies have been developed using AgGaSe<sub>2</sub> crystals [11].

# 4.4. Materials for wavelength conversion to the 2-5 μm band

One of the most important issues of the crystals besides the nonlinearity is the transparency range, i.e. the range in which the crystal can be used for wavelength conversion. It has to have a very low absorption both at the pump-wavelength and at the signal and idler wavelengths. Therefore, other materials than those used for the more common visible OPO have to be used when the IR-range is addressed. A high thermal conductivity is also favourable in order to avoid thermal lensing and other temperature related effects. Generally, nonlinear crystals are divided into two groups: oxide crystals and semiconductor materials. The oxides are generally transparent in the visible and near infrared while semiconductor materials can transmit from the near infrared through much of the mid-infrared region. Since the late 1960s it has been well known that a group of semiconductor crystals called chalcopyrites possess attractive properties such as high NLO coefficients and deep IR transparency. There have though been problems to grow large crack-free crystals due to highly anisotropic thermal expansion. Besides this problem, absorption and scattering due to defects limited the transmission in the near- to mid IR range. Recently these problems have been overcome by the development of a growth technique called horizontal-gradient-freeze (HGF) technique for chalcopyrites [12]. Some of these nonlinear materials are also available as periodically poled crystals. KTP (PPKTP), LiNbO<sub>3</sub> (PPLN) and RTA (PPRTA) are among the most common periodically poled nonlinear materials. With periodically poled materials one can utilise so-called quasi-phasematching (QPM) instead of conventional phasematching (see previous sections). Other applications for some of these nonlinear birefringent materials are as Pockel cells in EO q-switched lasers.

 $\beta$  phase of BaB<sub>2</sub>O<sub>4</sub> (BBO) is a common nonlinear crystal. It has relatively large nonlinear coefficients and good transparency in the visible region. Its large birefringence allows phase matching throughout the visible part of the spectrum, though this large birefringence also leads to birefringence angle and acceptance angle problems in some cases [13]. It is furthermore slightly hygroscopic. Frequency mixing allows generation of wavelengths down to 190 nm and BBO based OPOs can generate radiation up to 2.5  $\mu$ m. This crystal is also common as Pockel cells in Q-switched lasers.

LiNbO<sub>3</sub>, lithium niobate, was the first nonlinear crystal utilised to demonstrate optical parametric oscillation in 1965 [14]. It has relatively large nonlinear coefficients and large difference in variation of the ordinary and extraordinary refractive indices with temperature, making temperature tuning practical. LiNbO<sub>3</sub> is also available as PPLN, periodically poled lithium niobate.

KTiOPO<sub>4</sub> (KTP) is perhaps the most used OPO material for pumping with Nd:YAG lasers. It has large nonlinear coefficients and has a large angular acceptance, small walk-off angle and a high temperature bandwidth. It is biaxial and therefore allows a great variety of phase-matching conditions to be explored in order to find a large effective nonlinear coefficient and large acceptance angle. KTP is the most commonly used crystal for SHG of cw-, cw-mode locked and cw-q-switched Nd:YAG lasers at 1064 nm. Also KTP is available as periodically poled crystals, called PPKTP.

AgGaS<sub>2</sub> (AGS) is a chalcopyrite that has a good transparency in the mid-IR (0.5 - 13  $\mu$ m) and relatively good nonlinear coefficient. Its major disadvantage is its low damage threshold and high dn/dT value.

AgGaSe<sub>2</sub> (AGSE) is another chalcopyrite, which has been used as a frequency doubler for  $CO_2$  lasers. It is transparent between 0.71 - 18  $\mu$ m and has very large nonlinear coefficients, but due to poor thermal conduction and a nonzero absorption, heating may be a problem.

CdGeAs<sub>2</sub> (CGA) is one of the most promising nonlinear crystals available for mid and long wave infrared frequency conversions. It has one of the highest known nonlinear coefficients (236pm/V) and has thermal conductivity (0.042 W/cmK) sufficient for use in high average power applications.

ZnGeP<sub>2</sub>, (ZGP) This material has been shown to work very well as nonlinear medium for OPO applications in the mid-IR [12]. It can also be used as a frequency doubler for  $CO_2$  lasers using the second harmonic generation (SHG). It has an even larger nonlinearity than AgGeSe<sub>2</sub> but suffers from absorption in the near infrared ( $< 2\mu m$ ). ZGP has furthermore very good thermal characteristics, i.e. high thermal conductivity.

Materials used for frequency conversion into the IR regimes are summarized in Table 4.2. along with the crucial physical properties.

Table 4.2.	Some data of some	nonlinear crystals	Figures from	[15] unless stated.

Crystall	Nonlinear coefficients [pm/V]	Transparency range [µm]	Conductivity [W/mK]	Damage I [MW/cm <sup>2</sup> ]	threshold ] λ[μm]	τ [ns]
AgGaSe <sub>2</sub>	$d_{36} = 33$	0.71 – 19	1.0, 1.1	30	1.06	35
				25 10-20	2.05	50 150
AgGaS <sub>2</sub>	$d_{36}$ = 12.5	0.47 - 13	1.4, 1.5	0.2	1.06	15
				20	10.6	150
BBO	$d_{22}$ = 2.3, $d_{31}$ = 0.16	0.189 - 3.5	1.2, 1.6	50000	1.06	14
CdGeAs <sub>2</sub>	$ d_{36}  = 282 \pm 56$	2.4 - 18	4.2 [16]	38	10.6	160
CdSe	$d_{31}$ = -18, $d_{33}$ = 36	0.75 - 25	6.2, 6.9	50	2.00	20
KDP	$d_{36} = 0.39$	0.174 - 1.57	1.21, 1.34	8400,	1.06	1.3
				23000		0.2
KTA	$d_{31}$ =2.5, $d_{32}$ =4.2, $d_{33}$ =16.2	0.35 - 5.3		1200	1.06	8
KTP	$d_{31}=1.4, d_{32}=2.65, d_{33}=10.7$	0.35 - 4.5	3	3500	1.06	11
LiNbO <sub>3</sub>	$d_{22}$ =2.46, $d_{3l}$ =-4.64,	0.4-5.5	4.6	300-500	1.06	10
	$d_{33}$ =-41.7					
LiIO <sub>3</sub>	$d_{31} = 4.4, d_{33} = 4.5$	0.28 - 6	1.47	1200	1.06	12
RTA	$d_{31}$ =1.4, $d_{32}$ =4.6, $d_{33}$ =12.1	0.35 - 5.3		>400	1.06	10
ZnGeP <sub>2</sub>	$d_{36} = 75$	0.74 - 12	35, 36	60	1.06	100
				30000	2.94	0.11

# 4.5. Pump-sources

To obtain frequency conversion there has to be an original wavelength to be converted. This pump wavelength is for the OPO technique shorter than the desired output, since this photon is divided into two photons with less energy, i.e. longer wavelengths. A pump-laser at 1.0 –2.0 µm wavelength is suitable for OPO tuneability in the infrared depending on crystals and design of the OPO, see Figure 4.1. There is a degeneracy point at twice the wavelength of the pump, where the signal and idler have the same wavelength. The signal wavelength is always shorter or equal to this point while the idler wavelength always is longer or equal to the degeneracy wavelength. At its best one can expect a tuning range of the signal between ca 1.3 and 2 times the pump wavelength, whereas the idler wavelength is more than two times the pump wavelength (exactly two at degeneration point) and is often limited by the IR absorption in the crystal or the acceptance angle.

The pump source can be a laser operating at its fundamental emission wavelength. Tm and Ho lasers emit at this wavelength range although they are quite rare at the market. Other ways to achieve pumping for 3-5  $\mu$ m OPOs are by using frequency conversion from other laser sources (Figure 4.12). This can for instance be done with a harmonic generation of a CO<sub>2</sub> laser, or Raman shifting from shorter wavelengths sources, such as Nd:YAG lasers. Raman shifting lack good efficiency for larger shifts though and it is therefore more favourable to utilise an OPO pumped by a Nd:YAG laser at 1.064  $\mu$ m, as a pump-source for the IR-OPO. At this first stage it is not necessary with a tuneable OPO since it would complicate the construction and make the system less stable although this concept has been realized with non-critically phasematched OPOs [17]. It is more important to get a stable efficient source at a suitable wavelength to pump the tuneable IR-OPO. Therefore a stationary oscillator with a nonlinear material for an OPO pumped by a Nd:YAG would make the most attractive pumping source for the IR-OPO and this technique has been adopted by several groups.



Figure 4.12. Pumping of the OPO system with a pump laser and two successive OPO stages

Many different materials may be used as OPO materials for this first stage. KTP and PPKTP are attractive as nonlinear materials for this purpose. Since tuneability is of minor importance, periodically poled materials may be advantageous. PPKTP suites this task good due to high nonlinearity, low absorption at pump as well as signal

and idler frequencies, and high damage threshold. Other choices may be KTA or LiNbO<sub>3</sub>, see materials above for further details.

#### Choice of pumplaser and mode-locking scheme

When the OPO system and pumplaser are chosen to give a suitable output wavelength one has to consider the peak power (pp), pulse duration (pd) and pulse repetition frequency (prf). We will here limit our discussion to systems with pulse lengths shorter than ca 1  $\mu$ s and systems that are reasonably small (that can be taken outdoors). Basically, at high puls repetition frequencies the product pp \* pd \* prf is a constant, set by the physical means the gain medium of the pump laser can be loaded and subsequently emptied. The general "rules of thumbs" prevails:

High-prf system - mode-locked system

- *pd* <50 ps
- *prf*~100 MHz
- average power: 40-400 mW

Not so high prf - Q-switched/similar

- pd > ns
- *prf* ca 1-10 kHz
- average power >2 W

A Nd:YAG laser is thus a suitable choice for pump-source for a single or double-stage OPO. Various kinds of configurations of Nd:YAGs exist today for various kinds of applications. In our case a good beam-profile with a  $M^2$  – value close to 1 is essential as well as high power enough to pump the two-stage OPO. A poor beam-profile will not only decrease the efficiency of the conversion but may more easily damage the sensitive nonlinear crystals due to hot spots. Fairly high peak-powers are important in order to exceed the lasing threshold of the OPOs and to have a reasonable efficiency of the frequency conversion. This can be obtained with a Q-switched laser to yield pulse-lengths in the nanosecond range.

At the high PRFs required diode pumping of the Nd:YAG-rod is the most attractive choice. Flash lamps may be more suitable for a very high energy of single pulses or low *prf*. Diode pumping is though more efficient since the diode can be chosen so that the wavelength of the diodes matches the absorption band in the Nd:YAG rod. With a flashlamp lots of energy is wasted into energy bands where there are no absorption in the Nd:YAG, and thus only leads to heating.

To achieve a high *prf* >20 kHz an acousto-optic (AO) Q-switch is the most common technique to be utilised, even though lasers with electro-optic (EO) Q-switches have been reported to work with a pulse repetition frequency as fast as 20 kHz. AO Q-switches usually work in the range between 10 kHz and 100 kHz. Pockels cells are the most common EO Q-switches even though Kerr cells may also be used. To achieve an efficient OPO a high peak power is needed, i.e. the shorter pulse the better efficiency of the OPO. When choosing pulselength one should also consider the damage thresholds of the nonlinear crystals for OPOs. Thermal lensing in the laser rod is also an issue that should be considered when designing a laser. The effect of thermal lensing is unavoidable and will furthermore change with power and *prf*.

# Fiber laser pumping of optical parametric oscillators

During recent years high power continuous wave (cw) fiber lasers have been developed based on Erbium (Er), Ytterbium (Yt) or Thulium (Tm) doped single-mode (sm) fibres. The fiber laser has several attractive features in comparison to the more common diode- or flash lamp pumped solid-state laser. The beam quality from the fiber laser is excellent providing a nearly diffraction limited beam with  $M^2 < 1.05$  - 1.1. Fiber lasers based on Erbium or Thulium provide eye-safe radiation i.e.  $\lambda = 1.5$  or 1.8-2.0  $\mu$ m. Moreover, fiber lasers have high efficiency, are easy to handle and require no water-cooling. Other advantages include compact and robust package allowing for installation outside the laboratory environment. Most work on fiber laser has been concentrated on cw emission.

The telecommunication community and industrial applications such as e.g. micro machining have governed the developments of fiber lasers.

The common types of commercially available fiber lasers and their characteristic are depicted in Table 4.3. One interesting issue is whether fiber lasers can be used as efficient pump sources for generation of radiation in the mid-ir wavelength region using optical parametric oscillators (OPO). The maximum power (cw) currently available for the eye-safe fiber lasers is today approximately 15 W. Fiber lasers operating at  $\lambda = 1.08~\mu m$  with a cw power up to 100 W are commercially available. Since the average output power requirement for the DIRCM application is of the order 3-5 W in the mid-ir wavelength region neither Erbium nor Thulium cw fiber laser is suitable to be used as pump sources.

<i>Table 4.3.</i>	Commercial fiber	lasers*
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Туре	Wavelength	Power	Beam quality	Comments
	[µm]	[W]	$[M^2]$	
Ytterbium	1.08	100	1.1	
Erbium	1.5	15	1.05	Eye-safe
Thulium	1.8-2.0	15	1.05	Eye-safe
Ytterbium/pulsed	1.07	20 W	< 2.0	Pulse duration 150 -200ns,
				20 kHz prf, 0.5 mJ

A pulsed fiber laser operating at high pulse repetition frequency and with high average power is required to pump a mid-ir OPO efficiently. Unfortunately, pulsed fiber lasers based on single-mode fiber with limited mode volume have low pulse energy (of the order of  $\sim \! 10~\mu J$ ) due to amplified spontaneous emission. Using cladding pump procedures the modal volume of the fiber laser can be increased and pulse energies in the mJ range can be obtained. Pulsed Yt fiber lasers are manufactured capable of delivering 10 W in average power at 20 kHz pulse repetition frequency (Table 4.3).

Pulsed Yt and Tm fiber lasers are of interest for direct pumping of an OPO configuration. However, high average power of the order 10 to 15 W is necessary to provide the required output power in the mid-ir wavelength region. The requested prf is of the order of 10 to 30 kHz. Mode-locking techniques have usually been employed in pulsed fiber lasers to provide short pulse durations at high pulse repetition frequency. The average output power from mode-locking schemes is too low to be used in DIRCM applications.

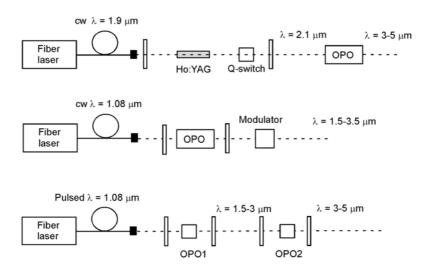


Figure 4.13. Pump schemes using fiber laser pump sources

In order to pump an OPO at  $\lambda=2.1~\mu m$  a cw Tm fiber laser can be used in a first step to pump a Ho:YAG oscillator containing an acousto-optic Q-switch. The output from the oscillator is subsequently used to pump an OPO stage (Figure 4.13). Another scheme is to use a pulsed Yt fiber laser operating at  $\lambda=1.08~\mu m$  to directly pump one or two OPO stages whereas the last OPO delivers radiation in the mid-ir region. Pulsed fiber lasers based on Yt capable of generating pulses with mJ energy at 10 to 30 kHz prf are available as shown above.

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Data from http://www.ipgphotonics.com

Continuous wave fiber lasers can also be used to pump optical parametric oscillators but the average output power after modulation will probably not be satisfactory for DIRCM applications [18]

Fiber lasers have been used for wavelength conversion in combination with optical parametric oscillators. Britton and co-workers utilised a Q-switched Er fiber laser and periodically poled lithium niobate (PPLN) to generate radiation from 1 to 4.4  $\mu$ m [19, 20]. Although, the parameters and experimental set-up were not designed for a DIRCM application the principles of using a fiber laser to drive an OPO was shown. Femtosecond pulses have been generated utilising PPLN and Er fiber laser and a fiber chirped-pulse amplifier [21]. An Yb fiber laser has also been used as pump source for difference frequency generation in the mid-ir wavelength region [22].

The technical requirements for using a fiber laser as a source for driving one or two OPO's for mid-ir wavelength generation include an average output power of the order 10 to 20 W, pulse repetition frequency above 10 kHz and pulse energies in the mJ range. The most favourable schemes utilise  $\lambda=1.5$  and 1.9  $\mu$ m sources. However, the available fiber laser sources capable of generating pulse energies in the mJ region with high prf operates at  $\lambda=1.08~\mu$ m. At this wavelength a diode pumped solid-state laser is a strong candidate for wavelength conversion into the mid-ir due to the proven technique. The fiber laser source offer advantages such as outstanding beam quality and no water-cooling requirements.

# 5. Literature survey

There are numbers of active groups that work in this field. In this section some different concepts and results by different groups will be described. At FFI in Norway they have suggested four different routes to achieve the desired output. They have recently presented five different concepts. The main idea is to utilise an OPO for the tuneability. Periodically poled litium niobate can be pumped at 1.064 nm and delivers 3-4  $\mu$ m. Due to absorption at longer wavelengths lituim niobate can not be used to generate light above 4 $\mu$ m. ZGP is then a good option and pumped at about 2  $\mu$ m it can emit at both 3-5 $\mu$ m and 8-10 $\mu$ m. ZGP absorbs at shorter wavelengths so it need to be pumped at about 2  $\mu$ m. The three main paths to the mid –IR are:

- a) Periodically poled litium niobate OPO pumped by an Nd:YAG giving 3-4 µm wavelength
- b) A tandem OPO pumped by a Nd:YAG. The crystals in the OPOs can be a periodically poled KTP giving 2.1  $\mu$ m, and a ZGP crystal pumped by the output from the first OPO. This concept can generate beams at both 3-5  $\mu$ m and 8-10  $\mu$ m.
- a) Ho, Tm: YAG laser directly pumping a ZGP OPO with 2–3 µm radiation.

# 5.1. Periodically poled LiNbO<sub>3</sub> OPO pumped with Nd:YAG

Quasi-phase matching is an attractive technique to birefringent phase matching for compensating phase velocity dispersion in frequency conversion applications [2]. Optical parametric oscillators with periodically poled LiNbO<sub>3</sub> pumped by 1.064 µm Nd:YAG lasers can both be tuned with temperature tuning and by accessing different quasi-phase-matched periods [3, 23].

At Fibertek an intracavity OPO with PPLN was constructed [24]. The pump source was a Nd:YAG laser Q-switched between 30 kHz and 100 kHz with the signal at 1.45 µm and the idler close to 4 µm.

Aculight Corporation has constructed an OPO based on periodically poled LiNbO<sub>3</sub>. A Q-switched laser at 1.064  $\mu m$  pumped it and the OPO was operated at idler wavelengths between 5.418  $\mu m$  and 5.592  $\mu m$  (corresponding to signal wavelengths between 1314 and 1324) by accessing different grating periods of the PPLN [25]. At this range there is a considerable absorption of the idler wavelength.

A PPLN OPO has also been constructed by Titterton et al. [26]. This system was designed for emission close to 4  $\mu$ m. Also this system used a acousto-optical Q-switched Nd:YAG laser as pump source with a prf between 15 kHz and 30 kHz. 2.8 W signal power and 0.87 W idler power was achieved with 7.8 W average pump power. The emitted laser power was limited by the size of the crystal and by crystal damage.

# 5.2. IR-OPO pumped with 2-3 μm laser

Conversion of 2  $\mu$ m with periodically poled LiNbO<sub>3</sub> s been shown by Hansson [27-29]. The output was tuneable between 3.2  $\mu$ m and 5.3  $\mu$ m with both temperature tuning and by accessing different quasi-matched periods. Absorption in LiNbO<sub>3</sub> limits the range further up in the infrared.

ZGP and AgGaSe<sub>2</sub> are two good crystals for wavelength tuning in the IR. Due to absorption in of wavelengths up to  $\sim$ 2 µm pump sources above this range must be used. Ho, Tm and similar lasers can then be used to pump these crystals.

At Lockheed Saunders a growth technique for chalcopyrites have been developed. They have demonstrated an OPO with ZGP pumped with a Ho:YAG at 2  $\mu m$  [30, 31]. This group has previously build a similar system pumped with a Ho:YLF laser at 2.05  $\mu m$  [32] and another one with a Raman shifted Nd:YAG laser pumping the ZGP OPO at 2.8  $\mu m$  [33]. In the Ho:YAG system the ZGP crystal was cut for Type I phasematching and placed close to the pump laser beam waist. Both input and output surfaces of the cavity were AR coated at 2 and 4.1  $\mu m$ . The resonator length was just 18 mm. Maximum achieved output for signal (3.8  $\mu m$ ) and idler (4.6  $\mu m$ ) was 4.24 W for 7.9 W Ho input power.

Recently, the operation of a ZGP OPO pumped by a  $Cr^{2^+}$ :ZnSe laser was demonstrated [34]. The ZGP OPO was pumped by a  $Cr^{2^+}$ :ZnSe laser tuneable between 2.2 $\mu$ m and 2.7 $\mu$ m. One of the advantages of this concept is that the absorption of the pump at this wavelength range is lower than at 2  $\mu$ m. The  $Cr^{2^+}$ :ZnSe laser itself was pumped by a Q-switched diode-pumped Tm:YALO laser operating at 1.94  $\mu$ m, and emitting 1.5 mJ 200 ns pulses at 1 kHz repetition rate.

#### 5.3. Tandem OPO

A frequently used configuration, reported by many groups is to use a diode pumped Nd:YAG laser and pump a KTP OPO, fixed at a signal output between 1.5 and  $2\mu m$ , which in turn pumps a ZGP OPO [35-39]. With this configuration essentially three IR wavelengths are generated: the signal from the first OPO, and the signal and idler from the final OPO stage. With a clever choice of crystals and phasematching angles most of the mid-IR can be covered. Cheung et al. [37] at TRW have build such a system with a Nd:YAG pumping a Type II degenerate KTP OPO converting 1.064  $\mu$ m pump beam to 2.13  $\mu$ m This OPO consists of six KTP crystals in walk off compensated configuration with a reflectivity of just 30% at 2.13  $\mu$ m to minimise back conversion providing 43 % conversion efficiency. This beam was pumping a Type I ZGP OPO to generate broadband radiation in 3.7-4.1  $\mu$ m (signal) and 4.4-4.8 $\mu$ m (idler). The pump laser was a so-called MOPA, Master Oscillator Power Amplifier. It was a cw diode array pumped Nd:YAG Q-switched laser yielding 38-40 ns pulses at 20 kHz pulse repetition frequency. Crystals were provided by Inrad and Lochheed-Saunders. The maximum output of this system was 14 W at 4.6  $\mu$ m when 25 W of 2.13  $\mu$ m was pumping the ZGP OPO. With a cavity length of 1.5 cm the OPO was running at multi mode with  $M^2$  = 4, but stretching the cavity to 4.5 cm  $M^2$  values of 1.8-2 were obtained.

At Q-peak they have developed a system tuneable between 1.5  $\mu$ m and 10  $\mu$ m, relying on a tandem OPO with KTA and CdSe respectively [17] pumped by a 1.053  $\mu$ m Q-switched Nd:YLF laser. The idler output from the KTA OPO was used to pump the CdSe OPO. This noncritically phasematched second stage OPO was tuned by the KTA OPO idler and its output was between 3.5-5  $\mu$ m and 8-10  $\mu$ m for signal and idler respectively. The pump laser delivered 30 ns pulses while the pulse-duration of the CdSe-OPO was 14 ns. The pump power from the Nd:YLF laser ranged from 50 mJ to 250 mJ giving a maximum output pulse energy from the CdSe OPO of 4.5 mJ.

At DSO National Laboratories in Singapore a tandem OPO, tuneable between 3  $\mu$ m and 6  $\mu$ m with its peak energy at 4.3  $\mu$ m has been constructed [40]. Four diffusion bonded walk off compensated KTP crystal operating at the degeneracy-point were placed within an A-O Q-switched diode pumped Nd:YALO laser cavity. The second OPO utilises a ZGP crystal and was placed in the cavity of the first OPO, although outside the laser cavity, see Figure 5.1.

Simultaneously 2.53 W at 4.3  $\mu m$  from the ZGP OPO, 7.2 W of 2  $\mu m$  from the first OPO stage and 33 W from the 1 $\mu m$  laser was achieved. The pulse repetition rate of this system was 5kHz.

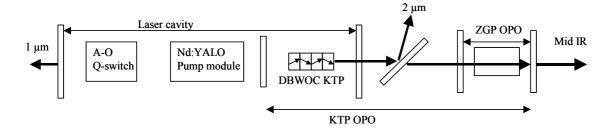


Figure 5.1. The integrated laser with the tandem OPO presented by Wu et al. [40]

In Table 5.1 some results from various OPOs from different groups are presented.

Table 5.1. Some different results from tuning in the IR

Pump laser	Nonlinear crystal	Tuning range	Output power/energy, prf	Pulse width [ns]	Reference
Nd:YAG 3 <sup>rd</sup> harmonic	BBO	0.412-2.55	4.7 mJ, 140mW	2.5	[41]
Nd:YAG 2 <sup>nd</sup> harmonic	KTP	0.7-0.9, 1.3-2.2	3 mJ		[42]
Nd:YAG 2 <sup>nd</sup> harmonic	BBO	0.94-1.22	1 mJ, 80kW (peak)		[43]
Nd:YAG	LiNbO <sub>3</sub>	1.50 (locked)	3 mJ	9.5	[44]
Nd:YAG	LiNbO <sub>3</sub>	2.5-4.0	4 mJ		[45]
Nd:YAG	PPLN	1.48 and 3.8 (locked)	2.8 W signal and 0.87 W idler at 30 kHz	35	[26]
Nd:YAG	KTP, ZGP	2.9 - 6.2	0.5 mJ		[38]
Ho:YLF ( $\lambda = 2.05 \mu m$ )	ZGP	3.45 - 5.05	1.6 W at 10 kHz	28	[32]
Nd:YALO	KTP, ZGP	3 - 6	2.5 W at 5 kHz		[40]
Nd:YAG,	KTP, ZGP	3 - 5	~0.75 mJ	20	[39]
Raman shifted Nd:YAG $(\lambda = 2.8 \mu m)$	ZGP OPO	4.7 – 6.9	150 μJ	5-7	[33]
Er,Cr,Tm:YSGG ( $\lambda$ = 2.93 $\mu$ m)	ZGP	3.8 – 12.4	1.2 mJ	100ns	[46]
Tm:YALO, Cr:ZnSe ( $\lambda = 2.2 - 2.7 \mu m$ )	ZGP	3.2 –3.6 (signal) 7.91-8.0 (idler)	130 μJ at 1kHz	~200 (pump)	[34]

# 5.4. Modelling of lasers

There are several tools for modelling optical systems available today. GLAD and several other optical modelling programs are frequently used tools for modelling optical systems. Some of these programs such as GLAD can also be used to model dynamic systems as lasers and OPOs.

A lot of effort has been put to model different kind of lasers, from diode pumping of YAG-rods to frequency conversion in all kind of tuneable OPO configurations. FFI in Norway has been working with these issues for a period of time and also constructed lasers based on their models with successful results [47-49]. One important issue that has been studied is the effect of resonator length on a doubly resonant OPO pumped by a multilongitudinal-mode beam, where it was found that it output energy had a significant maximum when its optical length matched that of the pump-source [39].

Smith et al. have modelled broad-bandwidth nanosecond optical parametric oscillators in plane wave configuration and included group velocity terms in the Maxwell equations along with a quantum noise model to address issues such as pulse-to-pulse fluctuations in signal and idler spectra and conversion efficiency [50, 51].

A triply resonant OPO based on AgGaS<sub>2</sub> have been examined by Zondy et al. [52]. They have introduced a theoretical TRO model including the thermally induced Kerr effect that accounts for the observed power limitations due to thermal lensing and dephasing.

#### 5.5. UV-lasers

Deep UV (sub 200 nm)

There is current a wide interest in "sub-100nm" laser is for the processing technology of silicon-based microchips. Shorter wavelengths are required to meet the future demands on sub  $0.1~\mu m$  line widths produced by lithographic means.

Ways to produce deep UV light at high powers has been suggested using so called "free electron lasers" (FEL), however, these lasers needs a source of high-energy electron beams (= accelerator facility). Premature stages of such lasers are studied by the U.S. This wavelength range is not considered to be "a serious threat" for military systems at the moment.

#### UV-blue (200 - 450 nm)

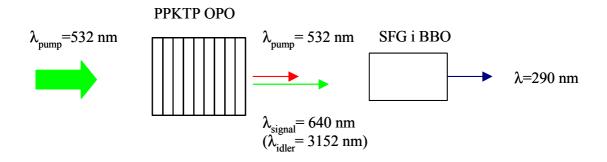
These wavelengths are useful in military systems particularly for chemical sensing (ozone, gas, biological agents via fluorescence detection). Potentially, these wavelengths can also be used for new sensor concepts where it comes to see difference between man-made targets and a natural background of "high clotter". It is anticipated that fluorescence and polarization signature is very specific if comparing for example paints and materials for signature reduction in the visible and IR, and different from the natural background. As is well known, night insect relies heavily on blue/UV spectrum for visual sensing.

These wavelengths are traditionally realized by employing gas-lasers based on  $N_2$ , Ar, Xe, and similar, however, usually resulting in a bulky and heavy laser design due to the high voltage excitating of a bulky gain medium. The "flexibility" in terms of wavelength tuneability is also very limited due to the often very narrow lines of the gain media. Optical components are also difficult to maintain at good quality at these wavelengths.

To realize these wavelengths with smaller and more tactical laser systems frequency conversion schemes from the NIR and visible is required. To achieve tuneability a combination of OPO and SHG and/or THG can be a feasible solution. There is a restriction of what nonlinear optical crystals that can be used; depending on how deep into the UV one needs top go and peak irradiance, etc. An advantage with these systems is that the pump lasers are made in the visible/NIR where compact diode-pumped lasers can be used as an efficient source with pulse energies of several joules can be realized at ns pulse ranges. This facilitates the nonlinear conversion process but sets high demands on the crystal optical quality. Relatively high conversion efficiencies can be reached (say, 5 - 50% depending on number of conversion steps.)

The most usual way to generate UV light in a compact design is to quadruple the light of an NIR/IR laser or to make sum-frequency generation of a pump-laser beam and its SHG produced in a parallel set-up. For Nd:YAG (1.064  $\mu$ m) as a pump the output wavelength alternatives will be 266 and 355 nm, for these alternatives, respectively. Conversion schemes of about 7% has been reached with such systems [53]. Such designs usually limit the available laser wavelengths (Nd-based systems are dominating).

Using only one pump-laser it is, however, possible to reach an arbitrary wavelength if a more complex frequency conversion process is utilized. An example based on a doubled Nd:YAG pump source is shown in Figure; the wavelength is here 290 nm that gives efficient absorption of oxone (remote sensing) as well as excitation of tryptophane, always present in biological warfare agents.



*Figure 5.2.* Wavelength conversion to the UV with a combination of an OPO with PPKTP and sum frequency generation (SFG) in BBO.

Polarization optics is here used to make appropriate polarization along the quasi-phasematched KTP crystal (PPKTP). PPKTP is here designed to generate the wavelength 640 nm. This is produced at relatively high efficiency (say 50%) and using a second, more UV-transparent OPO crystal like for instance BBO (see chapter 0), mixed with the pump (532 nm) to generate the desired 290 nm. This principle was first tested by A. Fix and G. Ehret [54]. However, using a slightly modified scheme for slightly different wavelengths. In any case, their conversion efficiency was ca 5% with maximum output of 19.5 mJ at 320. The conversion efficiency is of course very dependent on beam-qualities, optical quality, etc. The technique allows giving multiple wavelength output by arranging several OPO in parallel using the same pump (a strong source) to feed all conversion branches.

# 6. Current and future needs

# 6.1. DIRCM Systems - state of the art

- DIRCM systems are under intense development with a clear trend towards laser based jammers.
- DIRCM are developed for all kinds of platforms (vehicles, aircrafts and ships).
- So far open loop systems have been developed but systems with closed loop (CLIRCM) are now under development at the US Air Force among others.
- Nemesis flash lamp jammer + UV warner is in production.
- ATIRCM laser / flash lamp jammer is expected in production in 2002 mainly for large aircraft and helicopters.
- Systems for tactical fighters are under development (Northrops WANDA and Sanders TADIRCM). Both have successfully been tested in live fire tests against both LV and attacking missiles.

Systems for tactical aircrafts can become operational during the period 2005-2010. Advanced systems with damaging measures against the most qualified imaging IR seekers are estimated to become operational during the period 2010-2020. Systems for vehicles and ships may precede those for fast airplanes.

#### **DIRCM Systems – future challenges**

- In the future damaging measures will become important especially against imaging seekers.
- In USA studies of laser induced sparks as new countermeasures have commenced.
- Compact laser weapons for total sensor destruction will be developed, first in the band of the sensor and later on for out of band operation.
- Adaptive optics will be important for improving beam quality; both intracavity and extra cavity techniques will be used.
- Increased demand of multifunctionality of laser systems will lead to combined DIRCM, free space communication and active imaging capabilities.

#### New capabilities

It was recently announced that studies of new countermeasures, known as sparks, for countermeasures against missile threats had been stared. Very short laser-pulses (femtoseconds) are probably utilised in order to create sparks at very long ranges with reasonable laserpulse-energies. It has been shown that 1 mJ may be enough since the electric field will be very strong due to the short pulse length. Below two web-sites on the subject are cited:

http://www.systems.textron.com/sept28.htm

# Textron Systems Awarded \$13M for U.S.A.F. Aircraft Directed Energy Laser Applications (ADELA) Program.

Textron Systems announced today that it has been awarded a \$13M contract by the Directed Energy Directorate of the Air Force Research Laboratory, Kirtland AFB, New Mexico, to conduct experiments that assess the effectiveness of laser systems for aircraft self-protection against advanced anti-aircraft missile threats. The objective of the Aircraft Directed Energy Laser Applications (ADELA) program is to boost aircraft defense capabilities against current and emerging missile technology through the use of high-intensity lasers.

Under the five-year ADELA program, Textron Systems will design, develop and test lasers and laser beam pointing and tracking control systems at its Massachusetts facility. Textron Systems will employ IR sensor

technology to develop aircraft-mounted laser beam projection control systems. These systems involve the production of laser-produced plasmas (or laser "sparks") and other high-intensity laser effects.

"Laser sparks are proven to be highly effective in causing break-lock in older generation spin-scan and conscan missiles," said Dr. Daniel W. Trainor, Textron Systems Director of Lasers and Opto-Electronics and ADLEA Program Manager. "Laser spark also offers the countermeasure community an ability to disable and disrupt the operation of advanced (imaging) missiles," continued Trainor.

Previous tests funded by the U.S.A.F. have shown that the production of laser sparks in or near the focal plane of reticle-based missiles can be extremely effective in creating a false target, resulting in break-lock, within the missile's sensor suite. Tests included experiments with various missiles and hardware-in-the-loop. These tests complimented the numerous laboratory "strap down" break-lock experiments conducted at Textron Systems and at the Air Force Research Laboratory Directed Energy Directorate's Electrical Laser facility located at Kirtland AFB, NM.

#### http://www.knowlesreport.com/sample.htm

#### USAF Awards Directed Energy IRCM Contracts

The Air Force Research Lab's Directed Energy Directorate (AFRL/PL) at Kirtland AFB, NM, has awarded four contracts for directed energy technology that will support future aircraft infrared countermeasures (IRCM) applications. Known as the Aircraft Directed Energy Laser Applications (ADELA) program, the Air Force will investigate design issues related to damage and destroy IRCM approaches (see KR, 10/02/00, p. 1).

The Air Force awarded the four contracts for specific ADELA task areas. Task Area 1 covers laser effects testing, analysis and "threat negation" performance modeling. Georgia Tech Research Institute (Atlanta, GA) received \$1 million, and ITT Industries, Inc, Advanced Engineering and Sciences Division (Colorado Springs, CO) was awarded a \$4.5 million contract for this work. Task Area 2 calls for design, development and testing of laser source and beam-control systems. Textron Systems Corp. (Wilmington, MA) was awarded a \$13 million contract for this task. Finally, Task Area 3 covers system-level design, integration and performance trade studies. Raytheon Electronic Systems (Tucson, AZ) received a \$4.5 million contract for this work.

According to program officials, the Air Force hopes to capitalize on earlier AFRL efforts to generate a range of electro-optical effects that have shown promise against a many current IR threat technologies, including scanning and imaging IR seekers. Although ADELA will serve as a technology base to support a future IRCM system that could be installed on aircraft, the program will contain costs by also making use of existing IRCM systems to the maximum extent possible, said the officials. Specific technical challenges include the production of a laser that operates at the proper wavelength and provides optimal pulse formatting characteristics. Another challenge is the development of an advanced aimpoint control in beam control subsystems.

Work on the ADELA contracts will continue through 2006.

Consequences for the laser source development

- Improve present DIRCM lasers with respect to compactness and efficiency.
- Develop damaging laser in the 100 mJ + range
- Enhance beam quality
- Increase rapid tuneability or multiwavelength operation
- Develope multifunctional lasers for communication, DIRCM, active imaging applications and others
- In a longer perspective the femtosecond range should be addressed
- High power lasers for weapon-like applications
  - Diode pumped laser, diode lasers
  - Fibre lasers
  - Others

# 6.2. Future work

For DIRCM, the most attractive way today seems to be a OPO pumped by Nd:YAG or maybe Ho:YLF. Due to power and rep-rate a diode pumped Nd:YAG choice is most reasonable. It is therefore suggested that a suitable Nd:YAG pump-laser is bought and its properties are evaluated. To continue an OPO should be assembled with for instance KTP or PPKTP as nonlinear material in order to get a good source to pump an IR OPO such as ZGP or AgGaS or equal. The option with a PPLN OPO pumped by a Nd:YAG is also interested and should be further investigated.

There are several manufacturers of diode pumped Nd:YAG lasers on the market today. Some of them make industrial lasers for cutting. For such applications the size of the laser is seldom crucial. The MPS (Multi-Pass Slab) Gain Module<sup>TM</sup> by Q-Peak consists of two diode bars directly side-pumping a Nd:YLF slab crystal. Each diode has an attached collimating cylindrical lens for generation of a uniform-height pump beam in the Nd:YLF material. The laser beam is arranged, with the use of mirrors at each end of the slab, to pass through the crystal multiple times, sweeping out the pumped region. With the proper choice of mode size, the Gain Module<sup>TM</sup> can generate a high-power beam with a  $M^2$  of  $\leq 1.1$ .

Cutting Edge Optronics (CEO) is one of the suppliers of high power diode pumped solid-state lasers. They provide pulsed, Q-switched, and CW diode-pumped lasers with average powers of up to 250 W. One option would be to by a complete AO Q-switched laser. An alternative is to assemble a similar system with the laser head i.e. the diode pumped Nd:YAG rod from CEO. The advantage of this procedure is that the cavity can be designed for the task and the crucial size of the laser can be minimised. CEO has several module designs with different powers and beam qualities ranging from 10 W to 750 W CW power. A suitable choice for our application is the RB module that in different configurations delivers ca 75 W cw multi-mode powers. This pump module is in fact ordered and should be assembled with lasers mirrors and an acousto-optic Q-switch to make a suitable Nd:YAG pump-laser.

There are several manufacturers of nonlinear crystals for wavelength conversion. Different techniques are used to grow crystals and different companies use different techniques. Inrad is probably the company that makes the best ZGP with vary low losses utilising the so-called horizontal-gradient-freeze (HGF) technique. Other companies that manufacture nonlinear crystals are EKSMA, Crystal Associates and Raicol.

Future research on laser technology that can improve the capability of DIRCM systems are numerous and a few of the most relevant are listed below.

- Intracavity adaptive optics: Adaptive optics in terms of micromirror and/or other types of optical phase controlling devices can be used to improve the beam quality. Adaptive systems placed inside the laser cavity can be made to accommodate for temperature changes of the lasing media or other optical components to retain a good profile of the output. The response time for such an adaptive system does not need to be very fast, in the order of the heat build up and transfer, say, 10 ms 1 s.
- Extra-cavity adaptive optics: Integrated with the whole DIRCM system retroreflector signals can be used to make compensation of atmospheric disturbances such as turbulence. When this signal is analysed it can be used to compensate the output beam using a controllable phase mirror to improve the focusing on a distant target. The response time of such adaptive optical systems need to be rather fast, in the order of 1 kHz or even better.
- Laser wavelength tuneability: In order to optimize the capability to disturb or destroy an optical sensor it is critical to find the wavelength when the sensor is "open". One must have the possibility to tune the wavelength of the DIRCM laser system both in a search and track mode as well as in the jamming/destroying mode.
- Variation of output power: Certain applications needs high prf and relatively low output, for example when jamming seekers. For contermeasuring staring seekers and similar it is also necessary to give higher single pulses to ultimately destroy the sensing elements. A DIRCM system must hereby be able to switch between these two modes: high prf lower power; high puls energy single or few pulses.
- High output power: Increasing the power (> 100 kW) the sensor or even parts of its its platform/carrier (missile) ultimately will break down. New laser technologies that can handle such powers in small compact systems will always be interesting as a countermeasure. Small compact systems usually means solid state lasers. The cooling of the pumping/lasing medium is a problem that need to be overcome to develop such systems. If the laser is powerful enough the wavelength need necessarily not to be "inband".

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