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User report

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PRELIMINARY REPORT

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Report title

PROTECTION OF MID-INFRARED SENSORS AGAINST LASER RADIATION, PRELIMINARY REPORT

Abstract (not more than 200 words)

During the 1990’s the development of airborne Directed IR Countermeasures (DIRCM) has been intensified. A major thrust in military laser research nowadays is the development of suitable lasers to replace the present IR-sources in DIRCM-systems. R&D in laser technology therefore constitutes a potential threat against IR-missiles. This report presents different technical possibilities to counter the laser-threat in the mid-IR range.

FOI projects on Sensor Protection against Lasers have, during the last ten years, been focused on visible wavelengths and eye protection. Starting in 2001 the funding of activities aimed at protection against lasers in the IR-band will increase. This report will provide the basis and a starting point for this limited but purposeful three-year effort. In 2003 a protective principle for use in the IR-region will be demonstrated.

The most promising protective principles seem to be:

1. Absorption due to free-carriers in semiconductors
2. Light induced phase transitions.

Available information indicates that these principles have a reasonable chance of fulfilling the demands. We aim to successfully demonstrate one or both of these principles for protection in an IR-limiter during year 2003.

Keywords

laser protection, IR

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Rapportens titel (i översättning)

Skydd mot laserstrålning för sensorer i 2-5 µm området

Sammanfattning (högst 200 ord)

Under 1990-talet har utvecklingen av IR-motmedel intensifierats. En av de mest intensiva satsningarna inom militär laserforskning just nu är utveckling av laserkällor för IR-motmedel mot IR-jaktrobotar och IR-Lv-robotar. Forskningen, inom laserområdet, utgör därför ett potentiellt hot mot IR-robotar. Rapporten syftar till att ta fram tekniskt underlag för hur laserhotet i området 2-5 µm ska mötas.

Under de senaste 10 åren har forskning om skydd mot laser koncentrerats till synliga våglängder och skydd av ögon. Med start under år 2001 kommer vår forskning rörande skydd i IR-området att öka. Denna rapport kommer att utgöra startpunkt för en begränsad men målmedveten insats. Under år 2003 kommer en principdemonstration av ett skydd i IR-området att genomföras.

De mest lovande principerna verkar vara:

1. Absorption på grund av fria laddningsbärare i halvledare.
2. Strålningsinitierade fasomvandlingar

Tillgänglig information tyder på att dessa principer verkar ha en rimlig chans att uppfylla prestandakraven. Vi siktar på att demonstrera en eller båda dessa principer under år 2003.

Nyckelord

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1 Background

During the last third of the 20th century, infrared (IR)-missiles caused a majority of the military aircraft losses in combat. The early missile seekers were based on quadrant-detectors or reticle modulation of the target radiation.

Signature suppression and expendable decoys (flares) have been used in efforts to increase the survivability of the aircraft. Flares were particularly successful against quadrant detectors but the constant evolution of the seeker systems makes affordable flares insufficient. Even if the flare-technology continually evolves, it exhibits two inherent drawbacks:

1) New seekers have vastly improved hit probability. Especially the staring detector arrays offer good opportunities to use knowledge about the emission spectrum, the size, the temporal emission changes and the motion characteristics of the target to discriminate against flares.

2) The need to bring a large number of flares along on the aircraft is bound to reduce the possible mission payload.

These drawbacks were recognised early and active IR Countermeasures (IRCM) were first operationally employed during the Vietnam War. These early systems could well be fuel fired or electrically heated and possibly modulated by mechanical obscuration. The jamming is superimposed on the target signature. In quadrant-detector seekers the jamming signal had to overload the sensor in order to disrupt the acquisition of target position. In the reticle-based seekers a rotating reticle modulates the target radiation. The seeker electronics process the signal and deducts the target position based on analyses of the modulation. A mix of modulations by the reticle and the jammer is likely to cause the seeker to lose the target completely (optical break-lock).

The development of airborne Directed IR Countermeasures (DIRCM) continued during the 1990’s. One of the systems that were put into production was the NEMESIS-system, intended to jam IR-missile seekers. Due to the lack of suitable lasers, these systems were originally equipped with incoherent sources of radiation. Arc lamps can be modulated electronically and thus provide higher energy efficiency than combustion and electrical heating. A major thrust in military laser research nowadays is the development of suitable lasers to replace the present IR-sources in DIRCM-systems.

R&D in laser technology therefore constitutes a potential threat to IR-missiles. This report aims at different technical possibilities to counter the laser-threats in the mid-IR range.

FOI projects on Sensor Protection against Lasers have, for the last ten years, mainly been focused on visible wavelengths and eye protection. The laser protection activities financed by the Photonics program are still completely focused on visible wavelengths. For the Research and Technology part, however, a new research objective has been added. Starting in 2001, this program will increase the funding of activities aimed at protection against lasers in the IR-band. This report will provide the basis and a starting point for this small but purposeful three-year effort. In 2003 a protective principle for use in the IR-region will be demonstrated. The activities to reach this goal include interaction with universities and industries.

A particular problem when trying to incorporate protection against lasers in IR-seekers is that agreements often have been signed stating that the seeker may not be modified by the owner without the written consent of the manufacturer.

1.1 REPORT DELIMITATION

We generally limit this report to the mid-IR wavelength band (2-5 µm). The seekers and large number of FLIRs in the far IR-band (8-12 µm) could well be subject to hostile laser radiation but we only consider protective techniques in the mid-IR band.

The threat is threefold: jamming, damage and glint detection. The most severe threat is permanent damage putting the seeker out of operation. Jamming, on the other hand, is easier to achieve for the opponent. A problem for the operator of IRCM is to determine if an intervention has been successful. Glint detection is one way to detect, track and assess the status of a seeker. We elaborate a little further on the threat scenarios in chapter 2.

When it comes to possible protective actions and techniques we have a multitude of principles to choose from. The effects of some jamming sources may be countered merely by enhancing the seeker software. In other instances, a physical component may be the only solution to a jamming problem. Neither the damaging radiation nor the glint detection can be countered merely by software. This report will focus on physical principles/components for protection against jamming and damage. Some considerations about glint detection are also made, especially when evaluating different protective principles/materials.

We will neither discuss altered combat behaviour as a means of getting around anti-sensor-laser effects nor will we elaborate on clever seeker algorithms to defeat jammers.

Although this background chapter is focused on the high priority air to air and ground to air duels between aircraft and IR-missiles we will consider other scenarios in the chapters to come. Naval lasers, for instance, constitute a threat to anti-ship-missiles. There is also in army applications an increasing risk of laser jamming, e.g. against intelligent anti-tank-munitions. In chapter 3 we will discuss what kinds of threats that are likely to be encountered by a number of other sensors. Gunner's sights relying on FLIR-technology and IR Search and Track (IRST) sensors may be examples of sensors subject to laser radiation. This must be considered a highly disputable method for the opponent to avoid being detected by emitting detectable radiation. A more likely threat against reconnaissance sensors is damaging laser radiation rendering the sensors permanently useless.

2 Infrared laser countermeasures

DIRCM based on laser technology have been studied intensively during the last decade. Laser-based countermeasures have several advantages compared to passive techniques such as e.g. pyrotechnic flares and decoys. The high directivity, the high brightness, the possibility of being able to modulate the light, and swift re-targeting are some examples of favourable features of a laser countermeasure system. Directed infrared countermeasures can be used to jam or inflict irreversible damage in Electro-Optical (EO) sensors such as e.g. thermal imager and missile seekers. The laser technology also provides a longer range in comparison to passive techniques, which is of importance in studying the time scales related to the missile threat on airborne platforms. Technical demonstrator systems with laser countermeasures capabilities are presently evaluated for different military platforms. The most important applications, and also the most demanding from a technical point of view, is protection of airborne platforms from the heat-seeking missile threat. In particular, missiles operating in the 2 to 5 µm wavelength region are considered. In Figure 1 some of the most important laser wavelengths for DIRCM are depicted. Missiles can be either jammed or destroyed by laser countermeasures. An alternative but less effective method is to use a high power lamp to generate the radiation.

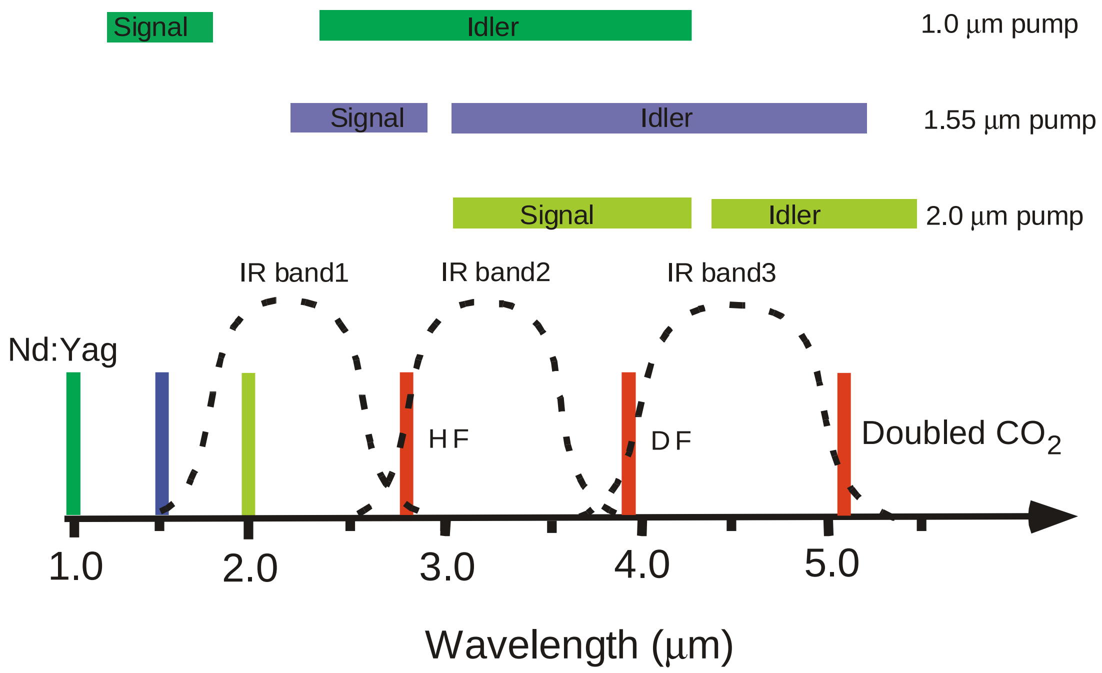

Figure 1 Important wavelength bands for DIRCM.

The simplest way to jam an EO-sensor such as e.g. missile seeker, thermal imagery or weapon sight is to modulate the radiation to generate a smart jamming sequence or saturate the detector. By using information from the radiation reflected from the target the optimal temporal shape of the jamming radiation can be chosen. One desired function of a countermeasure system is the ability to destroy the detector in the threat-sensor. Using pulsed lasers with pulse duration of 1 μs or less, the high peak power in the pulse may cause irreversible damage to the detector. The DIRCM systems studied for missile protection will in the future employ tuneable laser sources in the 2 to 5 μm region. Moreover, missile threats also exist in the longer 8 to 12 μm wavelength region. Apart from laser countermeasure systems particularly designed for countermeasures, other military laser applications exist which pose a threat to EO-sensors. For example, range finders and target illumination lasers for missile homing may cause damage both intentionally and unintentionally.

Some of the most important laser sources for DIRCMs are depicted in Table 1. Of particular interest as DIRCM for heat seeking missiles is the technology based on optical parametric oscillators (OPO's), see Figure 1. The technical requirements for mid-infrared (2 to 5 μm) solid state lasers include pulse duration in the nanosecond regime, pulse repetition frequencies (prf's) up to 10 kHz, pulse energies of the order of 50 to 250 mJ for damage purposes and rapid wavelength tunability.

2.1 JAMMING ELECTRO-OPTICAL SENSORS

Electro-optical sensors operating in the infrared wavelength region can effectively be jammed by exposure to lasers. Using laser countermeasures, the temporal appearance of the jamming signal is defined by using direct modulation of the laser source or an external optical modulator. The next generation of DIRCM systems employ *closed-loop* principles where active tracking is performed using the retro-reflex signal from the target. The target is identified and classified and subsequently the jamming signal is optimised for the particular ("smart jamming") target. The jamming source can also be tuned in wavelength in the region 2 to 5 μm or emit several fixed wavelengths simultaneously.

Table 1 Available laser technology for infrared countermeasures[1].

Laser	**λ** [µm]	t_p [s]	**PRF** [Hz]	**P** [W]	**Comments**
Nd:YAG	1.06	$5 \cdot 10^{-9}$ -cw	$<10^3$	$<10^3$	Pump source
Er-glass	1.54	$10 \cdot 10^{-9}$	<100	10	Pump source
Tm:Ho:YAG	2.01	$40 \cdot 10^{-9}$	≤10	5	Pump source
OPO	2.0-5.0	$10 \cdot 10^{-9}$ -cw	$<10^3$	10	e.g. KTP, $LiNbO_3$, ZnGeP
HF/DF	2.8/3.8	$200 \cdot 10^{-9}$ -cw	5-100	$<10^3$	Chemical laser
CO_2 (doubled)	5.0-5.3	$40 \cdot 10^{-9}$ -cw	$<10^2$	10	AgGaSe crystal
CO	5.0-6.0	cw		<100	Chemical laser
CO_2	9.8-10.6	$40 \cdot 10^{-9}$ -cw	$<10^3$	$<10^3$	TEA, rf-excited or chemical

The following abbreviations are used λ = wavelength, t_p = pulse duration, PRF = pulse repetition frequency and P = average power.

Depending on the target information, different jamming schemes can be utilised. The jamming signal causes detector saturation, inflicts a smart jamming or affects the automatic gain control (AGC) of the sensor. Present DIRCM systems use modulated high pressure Xe or Ar lamps to generate the jamming signal. However, tuneable continuous wave (cw) lasers are currently being developed for the next generation of DIRCM. Ideally, a mid-infrared cw laser, which can be modulated up to 10ths of kHz with an average power of approximately 5 to 10 W, should be employed for sensor jamming. The most important target for a DIRCM system is heat-seeking air-to-air or ground-to-air missiles. Modern infrared missiles developed during the next ten to fifteen years will use imaging sensors for homing, both scanning (one-dimensional) and focal plane arrays (two-dimensional), which will sustain simple jamming schemes.

2.2 Sensor destruction

Since the next generation of missile seekers ability to sustain jamming will be greatly improved, sensor destruction is an attractive feature of a DIRCM system. The detector is the most vulnerable component in an EO-sensor since it is located in a focal region. Incident radiation is focused to the detector surface or the pn-junctions in the case of back-plane illuminated detectors, causing high energy densities. By damaging the detector, completely or partly, the probability of defeating the threat missile increases. In older, but still operable missile threats, reticles are also sensitive components since they are placed in a intermediate focus in the optical path. A requirement for causing detector damage is to use a DIRCM laser emitting radiation at wavelengths coinciding with the operating wavelength band of the missile i.e. *in band* damage. A pulsed laser source is used to cause detector damage with pulse durations in the nano- to microsecond region. Laser damage studies of semiconductor materials and detectors have shown that the most severe damage is obtained using pulse

[1] Note, high energy laser (HEL) systems are not included.

durations in this region. With OPO techniques, pulsed irradiation can be generated in the 2-5 μm wavelength with a pulse duration of typical 10 ns.

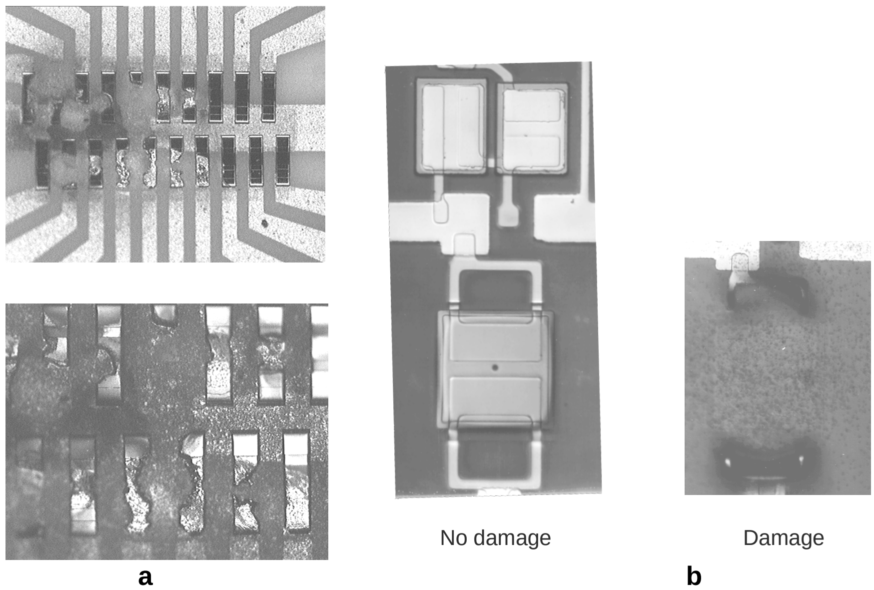

Figure 2 Example of laser-induced damage observed in (a) HgCdTe detector and (b) Silicon microbolometer detector.

An example of detector damage caused by pulsed laser irradiation is illustrated in Figure 2. The dominating damage mechanisms are melting and vaporisation of the detector material. Electronic damage due to current transients is another potential damage effect. Inflicting damage in scanning EO-sensors is more difficult compared to staring devices since synchronisation of the DIRCM laser is required in the former case. In staring sensors, on the other hand, the damage caused by a single pulse occurs in a localised region on the detector surface resulting in a limited number of damaged pixels. The pulse energies required to damage a detector in an EO-sensor at tactical ranges are in the order 50 to 250 mJ. Another threat for detector damage in sensors operating in the 3-5 μm window is laser weapons such as the DF-laser emitting radiation at 3.8 μm. Considering sensor protection, the hardest task is to protect the detector from damage when exposed to in-band short-pulsed laser irradiation. Since the pulse durations are in the order of ns to μs, the protection device needs a fast temporal response preventing the first pulse from reaching the detector.

2.3 INTERNATIONAL DEVELOPMENT OF DIRCM

Protection of large transport aircraft and helicopters has been given the highest priority and DIRCMs are in production in the USA and the UK. Smaller laser based systems for protection of small tactical aircraft are being developed. The critical technical issues for these systems are the tracking and pointing head and the tuneable laser source. Operating DIRCM jamming systems devised for tactical aircrafts will probably be available within 5 to 10 years. Considering systems capable of damaging the detector, posing a threat to imaging sensors, they will probably be operating within a timeframe of 10 to 15 years. In addition to DIRCM for protection of fixed and rotary wing aircraft, countermeasure systems for protection of vessels and fighting vehicles are also under development. Examples of DIRCM systems in production or under development are presented in Table 2

Table 2 International development of directed infrared countermeasures.

System	Country	Description
Nemesis, Northrop-Grumman	USA, United Kingdom	Protection of large aircraft, in production, jamming, open loop, life test successful, UV warning, high pressure lamp, “Wanda” laser (development),
ATIRCM, Lockheed-Martin	USA	Protection of large aircraft, UV warning, high pressure lamp for jamming, open loop, life test successful, upgrade “Agile Eye” laser, two-colour IR warning
LIFE	USA	Demonstrator system, protection of aircraft, closed-loop
FLASH	Germany, France	Demonstrator system, jamming and damage, transport aircraft, closed loop
MATES	USA, US Navy	Demonstrator system, protection of vessels, closed-loop, jamming and damage capabilities

Two systems, Nemesis and ATIRCM, are presently being evaluated for operational use. Nemesis consists of an ultraviolet (UV) warning system and a high power lamp for jamming purposes. In a planned upgraded version a laser is implemented which emits radiation at three different wavelengths in the infrared region (2.6-4 μm). The laser can be modulated with a prf of up to 10-20 kHz and emits an average power of approximately 3 W. The ATIRCM system consist of a suite of IR countermeasures including both passive pyrotechnic flares and a DIRCM based on a lamp (or a laser in an upgraded version). Both the Nemesis and ATIRCM systems are using open-loop principles for sensor jamming. The systems have been tested in live-fire tests and the results showed that missiles could be detected and defeated in a range of 3 up to 5 km. Advanced concepts for DIRCM (see Table 2) utilising closed-loop and a destruction laser are being studied in several countries. Apart from the USA, the UK, France and Germany, one can assume that both Russia and China have research and development programs aiming to manufacture effective DIRCM systems.

3 Protection requirements

We base our deduction of the protection needs on the assumption that a war-time opponent is reluctant to deliberately start emitting detectable radiation before he knows that he has been detected. The highest priority items for the opponent to counter using laser radiation would therefore be seekers and sights. To the authors’ knowledge there are no simple alternatives to laser countermeasures. Consequently, seekers and sights have to be protected.

In peace-keeping operations and non-war conflicts the priorities may change. Hampering video-recordings from sensors in the visible may be a way for a person or organisation to avoid being held responsible for an outrage in a supervised area. Information from IR-sensors, however, might not be conclusive evidence and sensor jamming or destruction in the IR-band is a lot more complicated than in the visible. This will probably make laser countermeasures at IR-wavelengths less attractive as compared with at visible wavelengths.

3.1 Seekers

The rapid R&D on lasers for DIRCM-systems intended to protect aircraft against IR-missiles imposes a severe threat to our missiles equipped with IR-seekers. Every reasonable possibility of protecting the seekers from optical break-lock should be investigated.

In the early days the IR-seekers were equipped with un-cooled PbS detectors. The wavelength band was in the 1.9 – 2.9 µm regime. Nowadays the more appropriate 3–5 µm band is utilised by e.g. cooled InSb detectors. A protective device should therefore be applicable at this wavelength band. There has been a shortage of suitable threat laser sources at these wavelengths but current developments in laser technology are rapidly changing this situation. Within 10 years we can expect to face a threat of pulsed (q-switched) to semi-continuous lasers with unpredictable wavelengths.

A couple of decades ago it was the reticle technology that took over from the less flare resistant quadrant-detector technology. A quadrant-detector could well be described as a very primitive staring detector array and is rather well suited to withstand laser countermeasures from the target provided that the dynamic range of the seeker is high enough.

It is interesting to note that besides other factors it is the treat from modern flare technology that is pushing the seeker industries away from reticle-based seekers towards the flare resistant staring detector array concepts. These arrays in turn are more susceptible to damage because a hostile laser is constantly focused on the same spot on the detector. In a scanning system the laser is only momentarily focused on the same spot on the detector. Furthermore, there is no direct need of focusing the radiation on the detector in a reticle system. The position of the target is estimated based on the seeker-specific modulation of the received target radiation. Since the reticle is positioned close to an image plane, the reticle is exposed to higher irradiances than the detector. Consequently, it is easier to damage the reticle than the detector material. The effect of reticle damage, however, is seldom as dramatic as the effects of detector damage.

As a starting point we thus identify three somewhat different protective needs for seekers:

3.1.1 Protection of staring arrays against damage.

To protect a ship or an aircraft from approaching missiles you want to make sure that your laser once and for all has permanently damaged the seeker, so that you will not have to go back to check if the missile has managed to lock on the target once again. All kinds of IR-missiles should be investigated with respect to their susceptibility to damage from IR-lasers. Staring arrays tend to be quite vulnerable since the laser radiation is constantly focused on the same spot. Laser pulse trains or continuous radiation will have time enough to transfer harmful energies to the corresponding pixel on the detector array. The threat could manifest itself as pulsed or continuous laser radiation. To achieve a reliable protection we have to look at both active and passive means of electro-optical counter countermeasures. Non-linear optics is one of the most promising fields in the protection of IR-sensors against damage from pulsed radiation. Active protection on the other hand with attenuators, agile filters and the like seems to be the way to go to protect against continuous and semi-continuous laser radiation.

3.1.2 Protection of scanning seekers against jamming.

As stated in chapter 1 we will not elaborate on clever seeker algorithms that can discriminate against flares and lasers based on a comparison of their characteristics as compared to knowledge about the target properties.

When it comes to countering strong jamming signals, one option is to increase the dynamic range of the seeker. This can be accomplished by attenuating the jamming radiation using active protection devices like variable attenuators, wavelength agile filters and the like. Technical means to accomplish this should be investigated

3.1.3 Protection against closed loop interrogation.

The aim here should be to investigate techniques to reduce the glint returns from the optical aperture of the missile.

3.2 SIGHTS AND OTHER ITEMS

Another way to defeat conventional weapon systems is to interfere with the actions of the gunner or sighting system. Consequently, sights are tempting targets for laser damage or jamming and are more likely to encounter laser threats than sensors for reconnaissance and target acquisition. Sights in the 3–5 µm band are comparatively rare at the moment but the number of FLIRs in this wavelength band is increasing and the number of sights is likely to follow in the future. The most recent trend here, as in seeker systems, is that staring detector arrays are replacing scanning systems.

Although the protection of IR-seekers and sighting systems has the highest priority we may not forget the other systems which are vulnerable to laser radiation. IRST-systems will probably occasionally be engaged by potentially damaging laser systems. The objective of these threats would be to pave the way for the opponent's less capable units. Once your opponent knows that he is detected, it is obvious that the effects of the radiation balances the drawbacks of emitting detectable radiation

4 Principles for sensor protection in the infrared region

Protection of EO-sensors operating in the infrared wavelength region can be divided into three different categories: static protection, active protection and self-activating materials (passive). Depending on the application the most appropriate protection method should be considered. The most important tasks for static protection components and design principles are to limit the transmission of radiation to the active band of the detector and to limit reflexes and stray-light in the optical path. Static protection can also be used to protect sensors against known, fixed wavelength threats. Active protection principles are mainly demanded in jamming scenarios or in order to protect passive components from lengthy exposures. Self-activating protection methods seem to be necessary to provide satisfactory protection against damaging laser pulses. Important issues related to the performance of the protective device are; time response, optical bandwidth and contrast ratio between the on and off states. From a practical point of view size and complexity may be important when deciding whether a protection principle is useful or not.

4.1 STATIC PROTECTION

Protection of EO-sensors from fixed wavelength exposure can be performed using static spectral filters[1]. Filters are used in several optical applications and the properties of new filters are improved continuously. Absorption or interference filters are the two most common types. One important figure of merit describing the attenuation of a static filter is the optical density (OD) defined as

$$OD = -\log\frac{I_t}{I_o} \tag{1}$$

where I_t is the transmitted intensity and I_o is the incident intensity on the filter. Using state of the art technology for filter design, attenuation levels in the order of 70 dB can be obtained. The optical bandwidth of the filter is an important design parameter. The static filters can be divided into two types: absorption and interference filters. The absorption filter relies on atomic or molecular absorption at a specific wavelength. The main drawback with absorption filters compared with dielectric interference filters is that the transmission/attenuation varies rather slowly as a function of wavelength. This makes it hard to design a reasonably transparent, multi-line rejection filter based on absorption. As a result absorption filters exhibit limited optical density close to the pass-band. Some absorption filters may become saturated at certain intensity levels of the incident light. However, they are relatively inexpensive and conceptually simple. Absorption filters have been manufactured using solids, liquids and gases as absorbents. Their main advantages are that their performance will not degrade by angle of incidence and they are not likely to cause severe glints or reflexes.

If we want rapid changes in transmission as a function of wavelength we have to chose interference filters. They are composed of stacks of dielectric layers on suitable substrates. Three major categories of interference filters can be defined; *bandpass*, *cut-off* and *narrow-band* filters. Examples of different filters are depicted in Figure 3. The band-pass filter is used to define a transmission region different from the substrate. The band-pass line-width is usually rather large. The cut-off and narrow-band filters can be used to reject specific fixed wavelength threats. Important properties of the interference filters are the bandwidth and the transmission in the non-blocking region. The interference filters have an angular dependence, which may be a disadvantage for some applications. Suitable substrates for interference filters designed for the IR-wavelength region are ZnSe, sapphire, silicon and germanium.

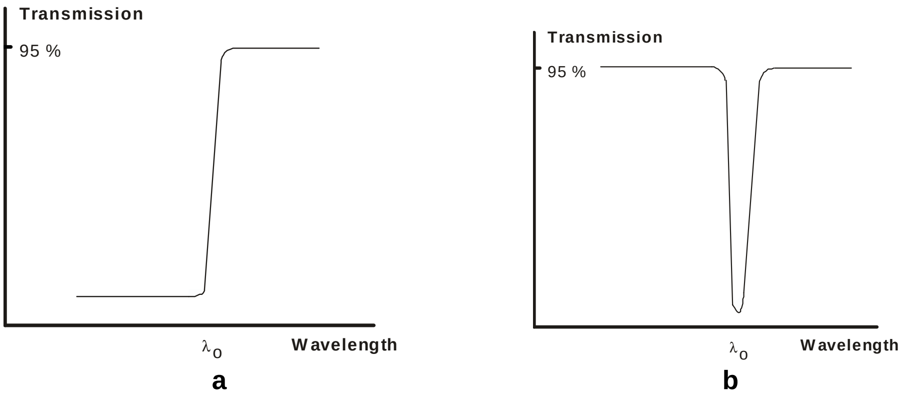

Figure 3 Characteristics of a low-pass (a) and notch filter (b).

The laser damage thresholds of the interference filters need to be carefully investigated before implementation as a laser protection component. Usually, however, the filter can be located in a non-focal region reducing the damage probability. A major disadvantage of static protection is the fixed wavelength limitation. If a broader optical bandwidth is rejected the sensor performance is affected. However, in some cases fixed wavelength rejection is a simple and preferable alternative for sensor protection, in particular for the protection of radiation outside the wavelength sensitivity range of the detector. A filter wheel arrangement could also be used if the time response can be accepted. For jamming threats the filter wheel approach may give satisfactory protection.

Filters inserted into the optical path may increase the retro-reflex of the sensor system thereby increasing the possibility of tracking down such a system. In order to avoid this problem the reflectivity of the filters should be as low as possible.

4.2 ACTIVE PROTECTION

Active devices are defined as components requiring an external triggering signal to activate the protection. The external trigger may be the first impinging laser pulse on the detector. A laser-warning device may also be used to initiate the protection. The time response of active devices is slow compared with self-activating materials. The active methods require more electronics compared to self-activating materials due to the external trigger (Figure 4). Moreover, external power may also be required for some active protection methods.

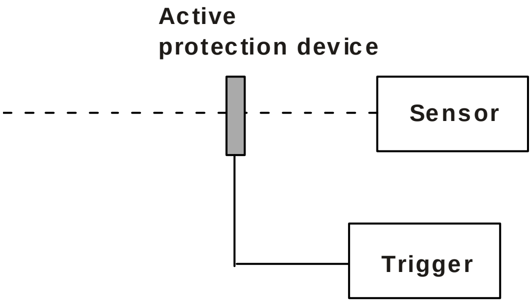

Figure 4 The principle of active protection of EO-sensors from laser exposure.

A major drawback with active protection is the slow time response, which makes protection against short pulses difficult. One possibility is to use shutters and filters as stochastic protection. For example, if a shutter is open 5 % of the time there will be a 95 % possibility that the first laser pulse will hit a closed shutter, given a non-correlated arrival of the laser pulses in relation to the closing and opening of the shutter. Stochastic protection, however, is a poor protection against pulse trains. If 100 randomly arriving laser pulses are considered, there will be a very low probability that all laser pulses will be stopped by the protection ($0.95^{100} \approx 0.006 = 0.6$ %). For this reason stochastic protection must always be supplemented by, e.g., some warning-activated protection. For low light levels the stochastic protection is less suitable since the average transmission will decrease with increasing protection capability. However, a stochastic protection may be useful against the first arriving laser pulses in a pulse train. Figure 4.5 shows the protection probability for a stochastic protection device, open 5 % of the time.

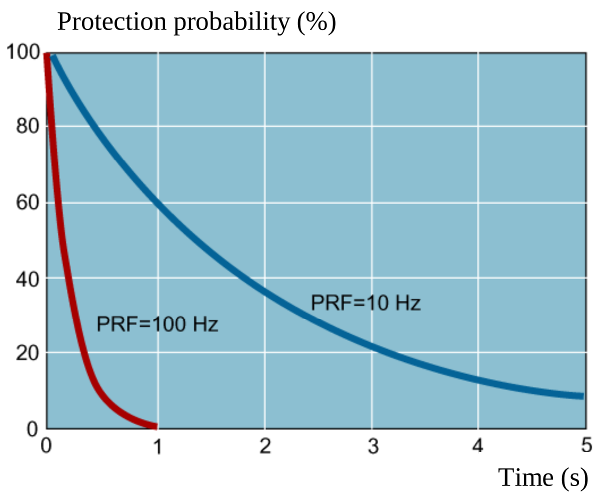

Figure 5 The protection probability for a stochastic shutter open 5 % of the time. The laser has a pulse repetition frequency (PRF) of 10 Hz (blue curve) and 100 Hz (red line). The protection probability is quickly decreasing with increasing exposure time and increasing PRF.

4.2.1 Mechanical devices

The simplest example of an active protection device is the mechanical shutter. The mechanical shutter has been utilised for sensor protection in several electro-optical sensor applications. The shutter will close the optical path completely and may also serve as a mechanical protection preventing the sensor from environmental effects. The mechanical shutter can not protect the sensor from a rapid single-pulse exposure without forewarning.

4.2.2 Electro-optical shutters

The principle for an electro-optical shutter is to alter the (linear or non-linear) optical properties of a material by an external electric field. Most commonly such a shutter will cover the entire field of view, but there is also the possibility to select parts of the field of view using a Spatial Light Modulator (SLM). Such a device is able to adjust it's optical properties locally, on a surface or in a volume. The principle of the SLM is illustrated in Figure 6.

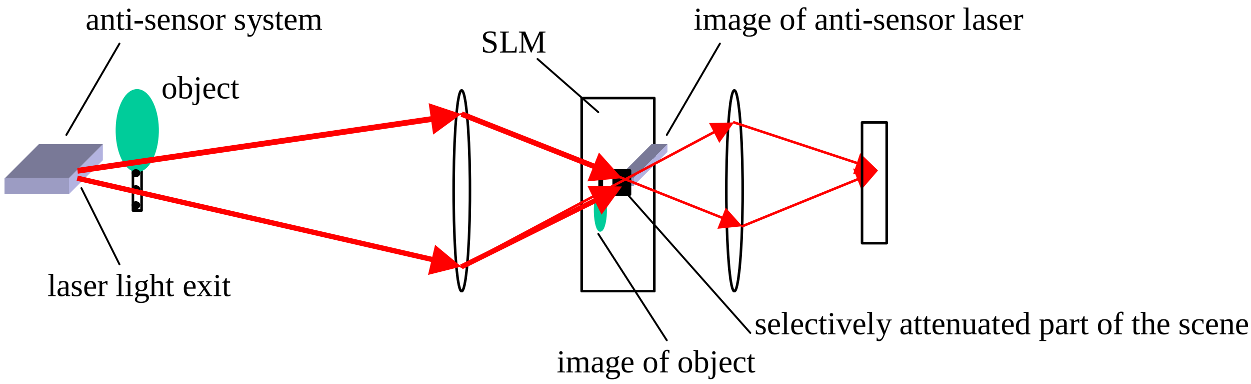

Figure 6 Schematic illustration of an SLM positioned at a focal plane in an optical system and, thus is able to selectively attenuate radiation from parts of the field of view containing the laser light exiting an anti-sensor system.

Liquid crystals

Liquid crystals are optical anisotropic materials for which the optical properties can be altered in an electric field. The basic physical principle is to alter the molecular orientation of the liquid crystal molecule as a function of the field. Dipole moments, spontaneous or induced, cause a torsion on the molecules, which alter their direction relative to the incident light due to the electric field. The optical birefringence, $\Delta n = n_e - n_o$, are in the order 0.1 to 0.3 for several liquid crystal materials. The effective index of refraction experienced by the light passing through a liquid crystal cell is changed due to the molecular re-arrangement. By altering the effective index of refraction a polarisation rotation or a phase modulation of the light can be obtained. The most common liquid crystal materials used as electro-optical shutters are nematic (NLC) and ferro-electric (FLC) liquid crystals. In NLC the optical properties altered linearly as a function of the applied electric field while the FLC materials are binary in nature i.e. switches between two binary states.

The response time of nematic liquid crystals are in the order 10 to 100 ms, while the ferro-electric materials alter state in the time interval 10 to 50 µs. The time response depends on the cell thickness, viscosity, temperature and the amplitude and temporal shape of the electric field. Driving voltages in the 5-35 V range are utilised to control the optical properties of an LC shutter. The simplest optical layout of a protection device based on liquid crystals is an

FLC cell placed between crossed polarisers as depicted in Figure 7a. In Figure 7b the attenuation of an FLC cell is shown in the "closed" state as a function of the direction of the incident light.

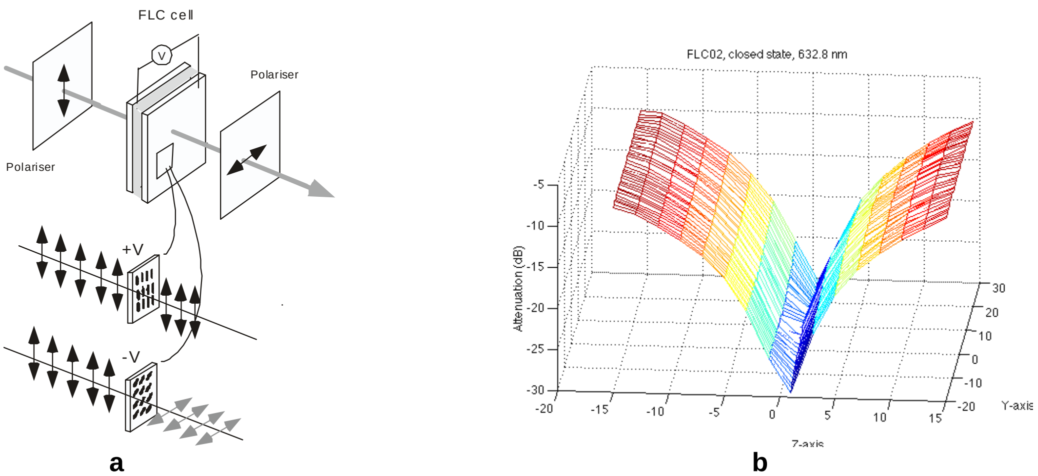

Figure 7 a) Principle of an FLC optical shutter. b) Attenuation for an FLC-shutter as a function of the direction of the incident light.

The use of liquid crystals for laser protection in the visible wavelength region has recently been studied[2]. The requirements for an LC based protective device were defined and we refer to this study for a more detailed discussion on LC devices for laser protection. Some of the requirements for LC protection devices are listed below:

- high attenuation in closed state
- high transmission in open state
- short transition time
- broad optical bandwidth
- wide acceptance angle.

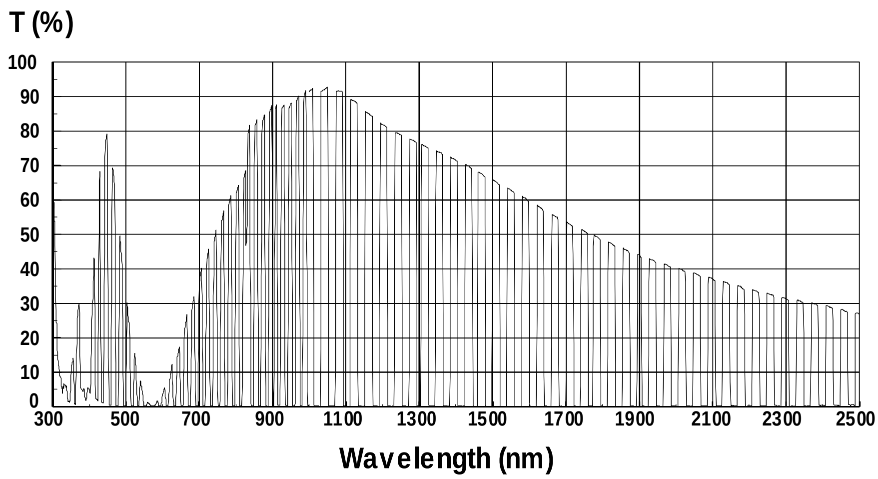

Figure 8 Transmission of a standard commercial FLC material in a 4 µm thick cell.

A critical issue using FLC materials as laser protection devices in the infrared wavelength region is the transmission properties. In general, FLC materials which exhibit acceptable transmission properties up to 2 µm can be identified. An example, showing the transmission of an FLC cell, is depicted in Figure 8. Shifting the wavelength into the mid-IR region, most

LC material start to exhibit molecular absorption due to vibrations. The transmission properties of several LC materials in the ir wavelength region have been discussed in the literature[3]. Another issue to consider is the limited optical bandwidth of LC devices making them unsuitable as laser protection devices in broadband applications. The polarisation dependent properties make liquid crystal devices unsuitable in applications where a high transmission is necessary for the sensor performance.

Electro-optical effects

The basis for the electro-optical phenomena is if the refractive index exhibits a non-linear behaviour as a function of the electric field. The two most used principles are the Kerr- and Pockels-effects. In the Pockels-effect the index of refraction varies linearly as a function of the applied field. In the Kerr-effect, on the other hand, the index of refraction varies quadratically as a function of the field. These two effects can be used to construct optical switches or shutters. For example, devices based on the Pockels-effect are commonly used as q-switches in laser cavities.

The electro-optical shutter component is commonly designed to work as a phase modulator or wave-retarder. The relative phase shift experienced when light is transmitted through an EO-component can be used to block the light. One way to perform optical switching is to place the material between crossed polarisers. The major drawback using electro-optical effects is the large control voltage required (in the order 1 kV). However, this voltage can be reduced significantly in smaller geometries and wave-guides. The time response of the electro-optical materials is in the order of MHz up to GHz for very small geometrical structures. The most commonly used electro-optical materials are ADP, KTP and $LiNbO_3$.

4.2.3 Tuneable filters

Another attractive feature of active laser protection principles is tuneable filters. The basic principle of a tuneable filter is to use active control to alter the filter properties such as e.g. the position of the pass band for a notch filter. A triggering device is also required to initiate the tuneable filter. The most common principles used for tuneable filters are Fabry-Pérot, Bragg, piezoelectric and acousto-optical tuneable filters as depicted in Figure 9. Tuneable filters can also be fabricated using liquid crystal devices. The tuneable filters can be designed to operate as reflective or absorption filters. The response time of the filters is often in the μs to ms region.

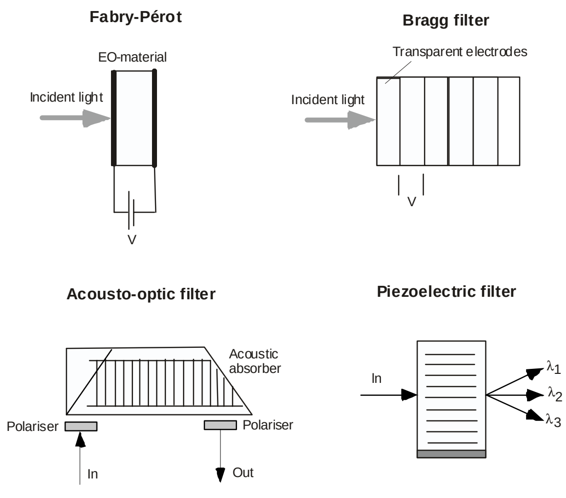

Figure 9 Example of methods for tuneable filters.[4]

In Table 3 some methods of active protection are shown. As pointed out above, the major drawback in using active protection infrared devices is that an external triggering signal is required. The time response for the active protection methods range from the order of micro- to milliseconds. Additional time delays for an active shutter device may be introduced via the trigger and the control electronics. Moreover, several of the active protection methods are limited in the optical bandwidth making them unsuitable as protection devices in the mid infrared wavelength region.

Table 3 Active protection methods (data from the visible wavelength region).

Method	Time response	Comments
Liquid crystal shutters	10–100 µs	Polarisation sensitive, FLC- or electro-clinic materials, drive voltages 5–30 V, temperature sensitive
Electro-optical shutters	< 1 µs	High drive voltages, polarisation sensitive (usually)
Tuneable filters	10–10000 µs	Bulky to implement, high-drive voltages, bulky control electronics
Mechanical shutters	~ ms	Slow time response, movable parts, high power consumption

4.3 SELF-ACTIVATING PROTECTION

Self-activating, or passive protection principles, utilise non-linear optical properties in materials or the fact that the fluence of the incident laser pulse is higher than a certain threshold value which activates the protection device. The self-activating materials behave as an optical switch or optical power limiter as illustrated in Figure 10. The polarisation of an optical material can be expressed as

$$\overline{P} = \varepsilon_o \chi \overline{E} = \varepsilon_o (\chi^{(1)} + \chi^{(2)} \overline{E}^1 + \chi^{(3)} \overline{E}^2 + ...) \overline{E} \tag{2}$$

where $\chi^{(n)}$ defines the nth order susceptibility. $\chi^{(2)}$ and higher non-linear susceptibilities define the non-linear effects used in passive protection materials and methods[5]. The non-linear effects have quadratic or higher order electric field dependency (defined by E in Eq.(2)).

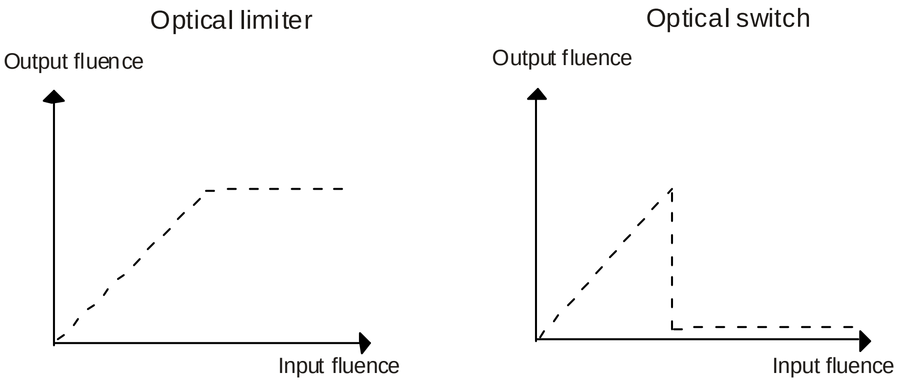

Figure 10 Schematic behaviour of self-activating protection devices.

If we consider the requirements for a self-activating protection device the following properties are considered the most important:

- fast time response
- high attenuation
- broadband action
- high damage threshold
- high transmission in the open state.

The temporal requirement for a self-activating laser protection material is a response time in the nano- to pico-second region. In following paragraphs, physical principles and concepts for self-activating laser protection materials in the infrared wavelength region are discussed. The materials employed in protection devices differ from those utilised in the visible wavelength region.

4.3.1 Optical absorption associated with free-carriers in semiconductors

The main non-linearities in semiconductors are known to be caused by the two-phonon and Raman transitions, the ac Stark shift, the free-carriers resulting from two-photon absorption or by photon energies nearly resonant with the band gap of the material[6,7,8,9]. At high excitation irradiance levels the non-linear effects originating from the two-photon-excited free-carriers have been shown to be most significant[8]. Two-photon transitions should be the most interesting since they will occur in the transparency region for low light levels and thus permit an IR sensor to function under normal conditions. The optical non-linearity, which arises from free-carriers in semiconductors are particularly important for applications because of the high degree of control which we have over the free-carrier densities, and therefore on the performance of devices which make use of them.

We are here primarily interested in the non-linearity, which occur when intense optical radiation pumps carriers from the valence band to the conduction band generating free carriers, i.e. carriers free to move inside a band. These transitions are either direct or indirect, depending on the energy band structure of the material. For indirect transitions the valence band and the conduction band can not be reached directly by an electron or hole without the assistance of a phonon, i.e. a lattice vibration, in order to make such transitions possible. The generation of free carriers can also occur by defect levels (by doping) in the band gap.

The change of irradiance as light is transmitted through the material will depend on the linear absorption, two-photon absorption and free-carrier absorption. The absorption of light by free-carriers is an accumulative process since the number of free charges will increase as light is absorbed in the material. This process can be compared to the absorption of light by excited states of a molecule. The irradiance transmitted through a sample can be expressed as[7 10]

$$\frac{dI}{dz'} = -(\alpha_o + \beta I + \sigma_{ab} N)I \qquad (3)$$

where α_o is the linear absorption coefficient, β is the two-photon absorption coefficient, σ_{ab} is the free-carrier absorption cross section, N is the density of free-carriers and z' is the penetration depth. It has been shown both experimentally and theoretically that β is strongly dependent on the band gap energy E_g according to[11]

$$\beta = K \frac{\sqrt{E_p}}{n_o^2 E_g^3} F\left(\frac{2h\nu}{E_g}\right) \qquad (4)$$

with

$$F(x) = \frac{(x-1)^{3/2}}{x^5} \quad (5)$$

where K is a material dependent constant, n_o is the linear refractive index, E_p is the Kane momentum parameter (≈ 21 eV) which is material independent for materials with a direct band gap, h is the Planck constant and ν is the photon frequency. A value of K=3100 was used in Ref. 11 from semiconductor data. From Eq. (4) we realize that materials applicable in the IR, i.e. small band gap materials, will have a larger value of β as compared with wide band gap materials. Also note the frequency dependence of β. Another possibility to increase the value of β could be to create an impurity level in the band gap close to the virtual level for the two-photon transition. The photo-generated carrier concentration is expressed as [7,10]

$$\frac{dN}{dt} = \frac{\beta I^2}{2h\nu} - \frac{N}{\tau} \quad (6)$$

where τ is the recombination time of the free carriers. The 2hν in Eq. (6) indicates that one electron-hole pair is created for every two absorbed photons. Diffusion processes are neglected in Eq. (6), which is valid as long as the diffusion time of free carriers is longer than the pulse width of the laser.

In order to find the solutions of I and N from the non-linear differential equations above the iteration method can be used. We assume that the last term including N in Eq. (3) is much smaller than the other two terms. In the first iteration step $I^{(1)}$ and $N^{(1)}$ can be obtained from Eqs. (4) and (6), respectively[7,8]

$$I^{(1)} = \frac{I_o \exp(-\alpha_o z')}{1 + \beta I_o L_{eff}} \quad (7)$$

$$N^{(1)} = \frac{\beta \exp(-t/\tau) \int_{-\infty}^{t} \exp(-t/\tau)\left[I^{(1)}\right]^2 dt'}{2h\nu} \quad (8)$$

where

$$L_{eff} = \frac{1 - \exp(-\alpha_o L)}{\alpha_o}.$$

Assuming that $I^{(2)} \approx I^{(1)}$ for the second iteration step, the irradiance $I^{(2)}$ at the exit surface of the sample can be obtained by substituting Eqs. (7) and (8) into Eq. (3):

$$\frac{dI^{(2)}}{dz'} = -(\alpha_o + \beta I^{(1)} + \sigma_{ab} N^{(1)}) I^{(2)} \quad (9)$$

$$I^{(2)} = I^{(1)} \exp\left[-\sigma_{ab}\int_0^{z'} N^{(1)} dz'\right]. \qquad (10)$$

When the laser pulse width is similar or longer than the carrier lifetime, the enhanced non-linearities based on the free charge carriers are expected because the rear part of the pulse experiences the accumulated two-photon-excited free charge carriers generated by the rising edge of the pulse. However, Eq. (7) should be valid as long as the laser pulse width is short enough as compared to the carrier lifetime (30-40 ps pulses were used in Ref. 8). The irradiance level should in this case also be below the critical level for free-carrier absorption.

β and I has been estimated for a few different materials using Eq. (4) and (7). For these calculations the parameter values of K and E_p were used according to these given above while the values of n_o and α_o were used according to Ref. [12]. Materials that could be useful in the 2-5 µm range are e.g. Ge, PbS and InAs with band gap energies at 300 K of 0.67, 0.37 and 0.35 eV, respectively. β as a function of photon wavelength is plotted in Figure 11, showing that InAs is a promising candidate with a high β-value in the 3-5 µm region. According to Figure 11 the maximum values of β were obtained at about 2.75, 4.5 and 5 µm for Ge, PbS and InAs, respectively. The output irradiance I from Eq. (7) was calculated at these wavelengths for the three different materials with the results shown in Figure 12. Despite the high value of β in Figure 11 for InAs the lowest saturation level of I was obtained for PbS in Figure 12. This is due to a rather high value of α_o for PbS as compared to the other two materials. In fact, the high value of α_o for PbS makes that material less useful for applications for which a maximum transmission is needed for low light levels. The transmission of light through Ge, PbS and InAs at the wavelength of maximum β is 100 (0.64), 12 (7.6) and 73 (0.51) %, respectively, with the transmission value including losses due to reflection in parenthesis.

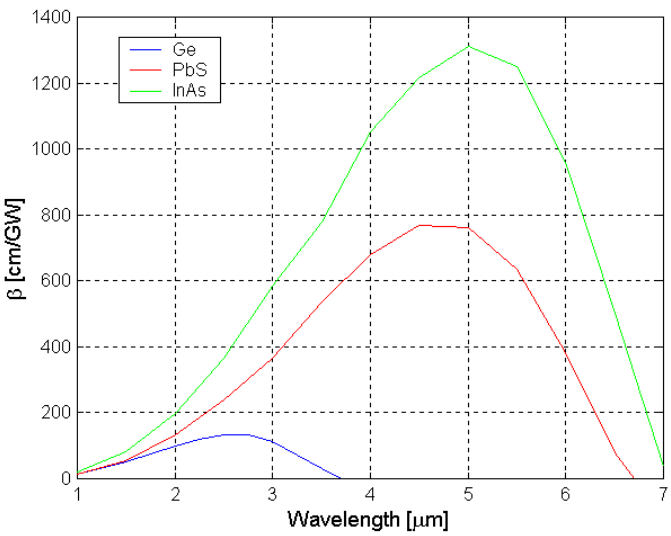

Figure 11 The two-photon absorption coefficient as a function of λ for Ge, PbS and InAs.

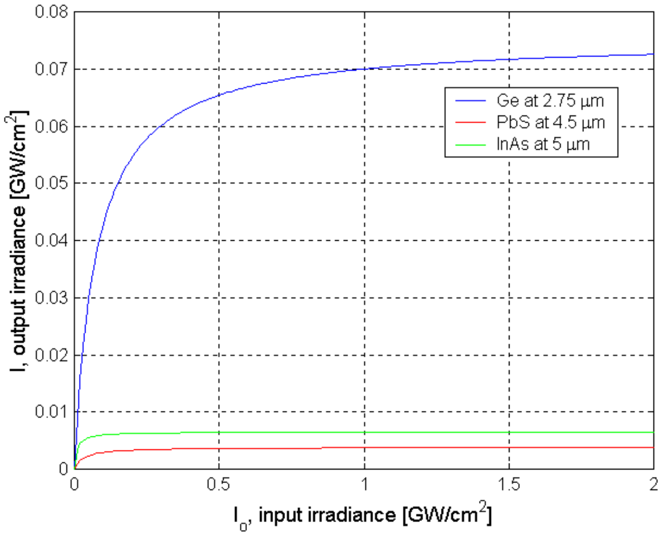

Figure 12 The input and output irradiance for Ge, PbS and InAs at 2.75, 4.5 and 5µm, respectively, calculated using Eq. (7)

The three selected materials according to the figure above are useful in the 3-5 µm range. In case the 8-12 µm range is of interest, materials such as InSb and MCT should be useful.

The significant non-linear effects present for semiconductor materials in the IR according to the above makes a more systematic investigation of several different materials interesting to find candidates suitable for use in laser protection. This should be followed by experimental measurements, e.g. using Z-scan experiments,[7,8] in which also various impurities and doping levels, together with non-doped materials, can be tested.

4.3.2 Light induced phase transitions

Physical phenomena related to light induced phase transitions of relevance for sensor protection are discussed in this paragraph. The most important physical processes are related to semiconductor to metallic phase transition, free-carrier effects and non-linear refraction. Using a broader definition, these materials are said to possess thermo-chromic effects. The preferred light induced transition switches the device from a transmissive to an opaque state.

Semiconductor to metallic phase transition

A semiconductor to metallic transition occurs when a material changes phase due to a increase in temperature caused by the absorbed laser radiation. In this case the optical material behaves as an optical switch and can be used for laser protection purposes. In the visible wavelength region, the material change colour as a result of the phase transition. Of particular interest for the infrared wavelengths are phase transitions based on thermally induced electronic transitions. Materials studied for optical limiting applications among this category are

1. oxides consisting of the transition metals Vanadium (V), Titanium (Ti) and Niobate (Nb).
2. mixed valence materials such as SmS and $TmSe_xTe_{1-x}$
3. non-stochiometric transition metal sulphides e.g. Fe_xS
4. ion conductors such as AgS and AgSe.

In this paragraph the discussion is focused on transition metal oxides since these materials have been studied in more detail.[13,14]

Vanadium dioxide (VO_2) exhibits abrupt changes in its optical properties due to a semiconductor-metal transition induced by a temperature increase in the VO_2 material. Usually a thin film of VO_2 is deposited on a suitable substrate, which transmits the incident radiation in a defined wavelength region. This radiation may increase the temperature of the VO_2 film if the irradiance is high, and at +68 °C a phase transition to a metallic state occurs. The physical principle of semiconductor to metallic transition in VO_2 is an increase in the d-d orbital overlap which causes a delocalisation of electrons and, hence, a metallic behaviour. The timescale for this process is in the order nano- to pico-second. Critical design parameters related to devices based on semiconductor-metallic phase transitions are: insertion losses, optical density, time response and damage thresholds. One problem experienced with the transition metal oxide films is the large number of stochiometric oxides that can be formed during the fabrication process. Different methods have been utilised in manufacturing thin films of VO_2 and V_2O_3. The most promising methods are based on sol-gel techniques and sputtering. Since the vanadium oxides can exist in several different phases the switching behaviour of the film depends largely on the purity of the oxide. The phase transition is recognised by an dramatic increase in the electric conductivity and values up to six order in magnitude have been observed in V_2O_3. An example of the refractive index variation as a function of the wavelength is shown in Figure 13. The significant difference between the semi-conducting and metallic state can be observed.

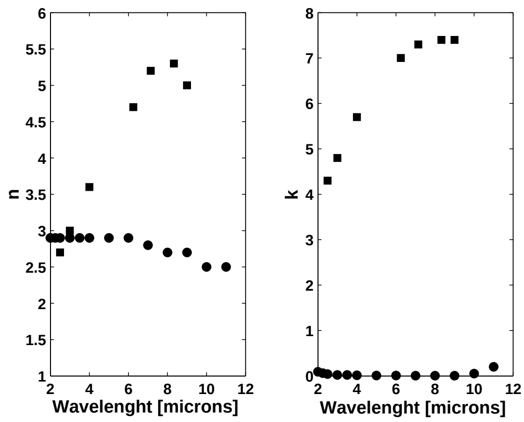

Figure 13 Variation of the refractive index (left) and extinction coefficients (right) for the semi-conducting (circles) and metallic phases (squares) of VO_2. From ref.[13]

The inherent switching time of VO_2 occurs on the pico-second timescale which suggests that VO_2 has a potential as a protection device for short laser pulse durations. The switching characteristics of a semiconductor to metallic transition device depends to a large extent on the heat transfer properties of the underlying substrate. A highly conductive substrate transfers the heat rapidly from the thin VO_2 film causing a recovery of the semiconductor properties. An antireflection coating layer may be incorporated on top of the VO_2 film in order to improve the transmissive properties. However, the AR-coating reduces the reflectance in the switched state, which degrades the efficiency of the device. Multi-layer configurations of VO_2 and AR-coating layers have been studied where the reflectance in the switched states increases.

An example showing the switching of VO_2 films on a silicon substrate is displayed in figure 14. The results show that a switching of the VO_2 film was obtained despite the poor quality of the oxide. In this case, thermal oxidation (by flowing O_2) in an oven was used to oxidise a vanadium film. The temporal behaviour of VO_2 polycrystalline films deposited on germanium substrates exposed to pulsed CO_2 irradiation has been studied[15]. It was suggested that the transition from semiconductor to metallic phase was dependent on the absorbed laser power. From previous studies of VO_2 it is concluded that the phase transition is purely thermally driven[15]. The substrate plays an important role in the switching characteristics of VO_2 films since the thermal conductivity of the substrate determines the rate of heat transfer from the film. Corbett *et al.* has investigated the spatial and temporal characteristics of thin VO_2 films[16]. They concluded that the evolution of the spatial beam profiles was dependent on the heat transfer mechanisms between the VO_2 layer and the underlying substrate.

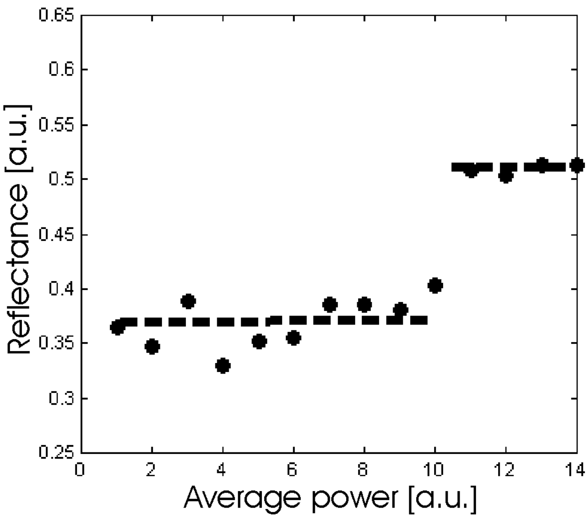

Figure 14 Example showing switching between two states for VO_2 at $\lambda = 2.8$ μm which was thermally oxidised and located on a silicon substrate. The optical quality of the oxidised VO_2 film was rather poor in this case.

Laser damage effects in VO_2 mirrors in the mid-infrared wavelength region have been studied thoroughly by Danilov and co-workers [17]. The VO_2 mirrors were exposed to both pulsed and continuous wave irradiation at 2.8, 3.8 and 10.6 μm. A model describing the switching characteristics of the VO_2 films was presented. Damage thresholds of 15-20 J/cm^2 were reported for pulse durations in the μs regime. Recently, VO_2 and Au-VO_2 films prepared by sputtering and sol-gel techniques have been studied for optical power limiting applications[18].

In this paragraph the discussion has been focused on thin films of VO_2 since they have been comprehensively studied. However, other material combinations exist which use the thermo-chromic effects to switch incident radiation. Donor and acceptor atoms, e.g. F, Mo, Cr or Ga, alter the properties for the phase transition. The thermo-chromic materials need to be carefully characterised and evaluated before an implementation as a laser protection device can be considered. Critical issues to address are response times, substrate materials, transmission and reflection coefficients in the two separate states, and wavelength dependency. New material combinations should also be investigated in order to improve the performance of the optical switch. Multi-layered structures may show a better performance with respect to the switching behaviour.

4.3.3 Sacrificial limiters

A sacrificial limiter is a simple concept for a broadband laser protection device where the material is damaged by the exposure. An example of a sacrificial limiter concept is if a thin metal layer is deposited onto a suitable transmissive substrate and the metal layer acts as a reflecting mirror if the incident radiation is below an activation threshold (Figure 15). The metal layer is a sacrificial layer, which is damaged if the fluence of the incident laser pulse is higher than the laser damage threshold. Usually the metal film has a thickness in the order of 20 to 100 nm. When the damage threshold is exceeded morphological damage occurs on the surface causing the incident radiation to be partly transmitted through the substrate and diffusely scattered. An important criteria of the metal layer is to exhibit a high reflectance in the non-activated state and thereby reflecting all incident radiation onto the detector. The sacrificial limiter is placed close to a focal region in the optical path or in an intermediate focus. Thus, the incident threat radiation is focused onto the surface of the metal film. The damage mechanisms are dependent on the pulse duration but melting, vaporisation and plasma breakdown are the dominating effects. The main problem with sacrificial limiters based on the evaporation of metal films is the remaining reflectivity of the substrate once the metal is evaporated.

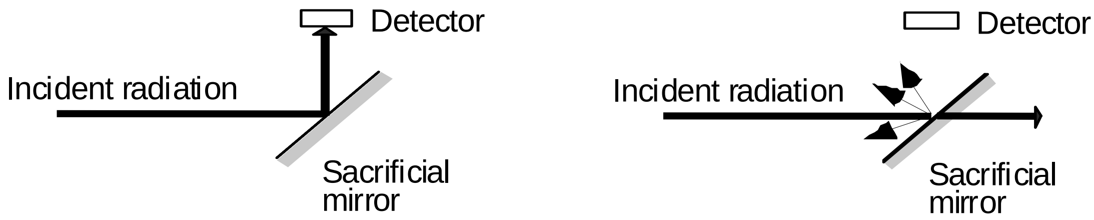

Figure 15 The principle of a sacrificial limiter consisting of a thin sacrificial metal film on a transmissive substrate. In the operating state the mirror is reflecting the incident radiation onto the detector (left). Above the damage threshold the radiation is transmitted and partly scattered (right) protecting the detector.

The protection process of the sacrificial limiter is irreversible and an opaque dot in the field of view will be the consequence of every exposure that activates the limiting mechanism. The sacrificial part of the limiter will have to be replaced in order to completely re-activate the sensor. Different types of mechanical solutions, such as e.g. “filter-wheel” arrangement, can be used to re-activate the sensor. The irreversibility of the sacrificial limiter is a major drawback when using them as laser protection devices in infrared target seekers. The laser countermeasure system will probably be able to locate the seeker after the sensor has been re-activated.

Several critical parameters need to be considered when using sacrificial limiters as laser protection devices. The reflectance in the non-damaged state is important in order to maintain the sensitivity of the EO-sensor. A reflectance larger than 90% is required. Upon activation of the sacrificial limiter the attenuation should be large enough to protect the detector from damage. The reproducibility of the activation threshold of the device should be high, i.e. the influence of the manufacturing process should be small regarding defects in the thin metal film. Another parameter of importance is the temporal shape of the incident threat pulse. The damage threshold of thin metal films is dependent on the temporal shape and duration of the laser pulse. Moreover, the wavelength of the incident radiation may also affect the damage threshold of the metal film.

The sacrificial limiters can be implemented in single-pass (Figure 15) or double-pass configurations (Figure 16). The incorporation of a double-pass configuration in a real optical system, however, may prove impossible. The advantage of using a double-pass configuration is the increased attenuation[19]. DiCillo and co-workers studied laser damage in thin aluminium (Al) films for application as optical fuses[19]. They obtained a maximum attenuation in the order of 10^4 or more for the incident pulsed radiation above the activation threshold. By using a double pass configuration the attenuation was significantly improved. It should be pointed out that the double-pass configuration is critical with respect to the design parameters. It is necessary to ensure that damage is invoked at the sacrificial mirror at the time of the double-passage of the light, otherwise the light is reflected into the detector.

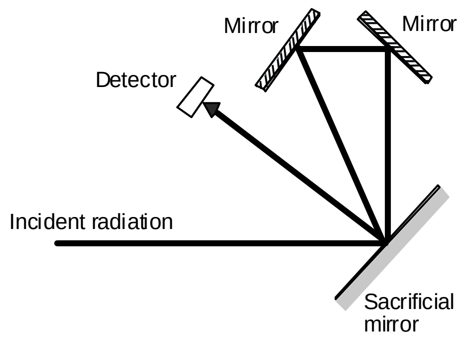

Figure 16 Example of an sacrificial limiter in double-pass configuration using two additional mirrors.

The dynamics of optical damage in thin Al films have also been studied[20]. Theoretical and experimental results for pico-second laser pulse exposure on Al films were presented. The results indicated that thin metal films can be used as laser protection devices. In a recent study different types of metal films for sacrificial limiters applications were investigated by modelling and experimental investigations.[21] Aluminium and tin metal films were studied experimentally after modelling the vaporisation rate for different metal films. Tin exhibited a faster vaporisation rate than aluminium when exposed to pulsed laser irradiation. Several models describing laser induced damage to thin metal films on different types of optical substrates have been presented in the literature.[22] These models can be utilised to evaluate the potential for different metal films and substrates for laser protection applications.

The major advantages of sacrificial limiters are the simplicity of the optical arrangement and broad-band operation of devices. An irreversible damage mechanism requires replacement of the protection device upon re-activation of the sensor as mentioned above. Other complications include pulse duration and wavelength dependency.

4.3.4 Non-linear focusing or defocusing

Self-focusing and defocusing are optical non-linear effects which can be used in optical limiting applications. This non-linear refraction effect in a material can manifest itself as beam broadening or narrowing in the far field, i.e. causing the focusing or defocusing which is dependent on the irradiance input. Figure 17 illustrates these concepts.

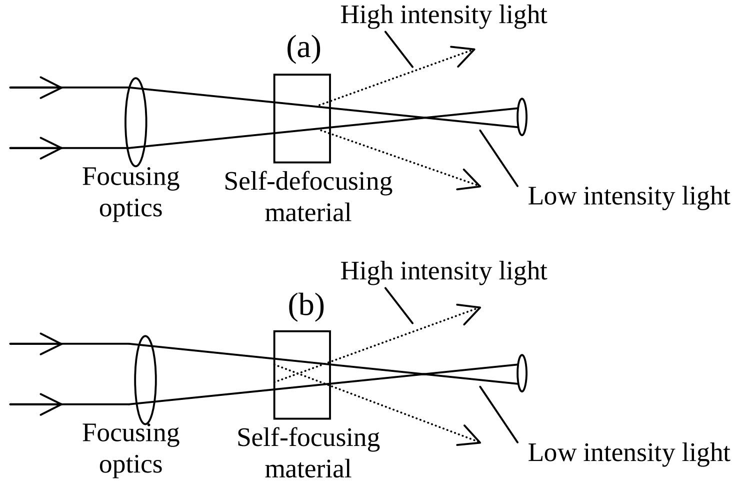

Figure 17 The concepts of self-defocusing (a) and self-focusing (b).

A useful experimental set-up for measuring the non-linear refraction effect is the Z-scan method. In such an experiment when using an aperture positioned after the sample (see Figure 18), an increase in transmittance followed by a decrease in transmittance (peak-valley) denotes a negative non-linear refraction (self-defocusing), whereas a valley-peak configuration implies a positive non-linearity (self-focusing). If the aperture in the Z-scan set-up is removed, i.e. detector D2 is collecting all the transmitted light (a so-called open aperture Z-scan) this will result in a flat response for a purely refractive non-linearity. However, in the presence of non-linear absorption (see the above) the response will appear as an inverted Lorentzian with a minimum at z=0.

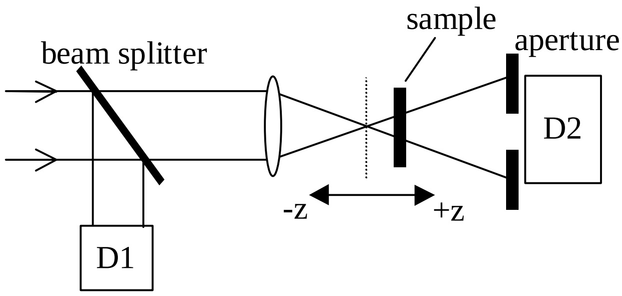

Figure 18 Z-scan experimental set-up. The ratio of the irradiances measured by the detectors D1 and D2 is measured as a function of sample position z.

Assuming that both bound and free carriers cause the change in the index of refraction, we get the relation[8]

$$\Delta n = \gamma I + \sigma_r N \tag{11}$$

where γ (m^2/W) is the non-linear index that is due to bound electrons and σ_r is the change in the index of refraction per unit photo-excited charge-carrier density N. γ is related to the real part of the third-order susceptibility, $\chi^{(3)}$, the speed of light, c, the refractive index in the absence of free-carriers, n_o, and the free-space permittivity, ε_o, in such a way that[10]

$$\gamma = \frac{3}{4n_o^2 c\varepsilon_o}\,\mathrm{Re}(\chi^{(3)}) \tag{12}$$

The term in Eq. (11) related to the non-linear refraction due to bound electrons (γI) is also called the electronic Kerr effect and it will be dominant at relatively low irradiance levels, whereas the free-carrier refraction ($\sigma_r N$) will dominate at high irradiance levels. Since the carrier non-linearity ($\sigma_r N$ in Eq. (11)) is proportional to a temporal integral of I^2 (Eq.(6)), this will be an effective fifth-order non-linearity. In the case of two-photon absorption this fifth-order non-linearity is a sequential $\mathrm{Im}(\chi^{(3)})$ process (i.e. two-photon absorption) followed by a $\mathrm{Re}(\chi^{(1)})$ process (i.e. a linear index change from the carriers). Since the electronic Kerr effect is a third-order effect the non-linearity due to carriers generated by two-photon absorption will dominate above a certain irradiance level.

Experiments and calculations have shown that the maximum of γ will occur close to the resonance for two-photon absorption and that it will change sign from positive to negative when the photon energy is greater than about 70 % of E_g. Since γ has been shown to have a

E_g^{-4} dependence,[11] a strong non-linear refraction is expected for semiconductors with a small band gap.

A problem with self-focusing is, however, that it may cause damage to the non-linear material due to the high energy density in the focal spot. Self-defocusing should for this reason be preferable.

4.3.5 Photo-refractive optical limiting

The photo-refractive effect can be used for sensor protection utilising materials acting as non-linear optical limiters. In photo-refractive materials, free charges are liberated due to high intensity laser irradiation. Changes in the space-charged field because of the radiation causes alterations in the index of refraction. Laser damage thresholds and the time response of the photo-refractive effect are important issues related to the use of photo-refractive materials in optical limiting applications. In the simplest concept, the photo-refractive material acts as a volume grating. Beam fanning[5,23] is a phenomenon that has been discussed in relation to optical power limiting. The beam fanning effect is described as a beam entering a photo-refractive material and causing a set of asymmetrical beams to be formed after passing through the photo-refractive crystal.

The method of beam fanning can be improved by splitting the incident radiation into weak and high intensity beams before entering the photo-refractive crystal. The two beams are coupled in the crystal and the high intensity radiation is transferred to the weak beam path and thereafter dumped (see Figure 19). The process is dependent on highly coherent radiation i.e. broadband irradiation is not coupled to the beam dump. The optical limiter is activated by high intensity coherent radiation. A disadvantage of optical limiters using the photo-refractive effect is the rather slow response time of the material since diffusion processes are the governing mechanisms.

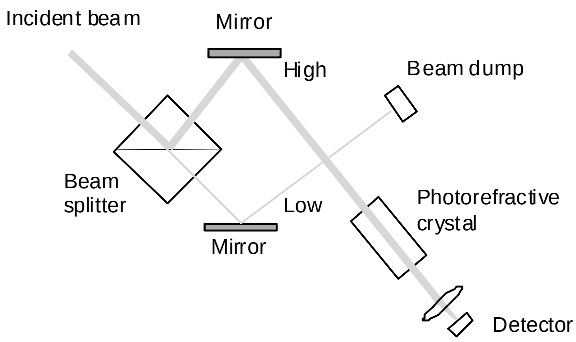

Figure 19 The principle of photo-refractive optical limiting using the beam-fanning method.

4.3.6 Plasma shielding

In general, a plasma is a medium with equal concentrations of positive and negative charges, of which at least one charge type is mobile. An electron plasma will be created if the energy of the incoming irradiation field is high enough in order to totally or partially ionise the atoms of, for example, a gas or a solid material. If the plasma is generated by a laser hazard pulse, the plasma will interact with the remainder of the pulse via absorption, reflection and scattering. In order to discuss the properties of a plasma we need to introduce the plasma frequency, ω_p, which is given as [24]

$$\omega_p = \frac{Ne^2}{\varepsilon_o m} \qquad (13)$$

where ε_o is the dielectric constant in vacuum, N is the free electron concentration, e the electron charge and m the electron mass. The dielectric function of a free electron gas is expressed as

$$\varepsilon(\omega) = 1 - \frac{Ne^2}{\varepsilon_o m \omega^2} \qquad (14)$$

with ω as the frequency of the radiation field. Thus, we can express the dielectric function as

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}\,. \qquad (15)$$

If ε is real or $n^2 >> \kappa^2$, where κ is the extinction coefficient ($\kappa = \alpha_o \lambda / 4\pi$), then $\varepsilon = n^2$ which can be used in the expression of the reflectance R

$$R \approx \frac{(n-1)^2}{(n+1)^2}\,. \qquad (16)$$

These expressions imply that frequencies below ω_p will give a negative value of ε, i.e. the radiation is totally reflected, while frequencies above ω_p will be transmitted through the plasma. For example, metals with $n=10^{22}$ cm^{-3} will have ω_p of about 6×10^{15} Hz, thus, visual light will be reflected while transmitting light in the UV. Figure 20 shows a reflectance spectrum of InSb with different electron densities. The advantage of using a semiconductor material rather than a metal is that it is possible to control the electron concentration and ionisation energy by doping in the semiconductor.

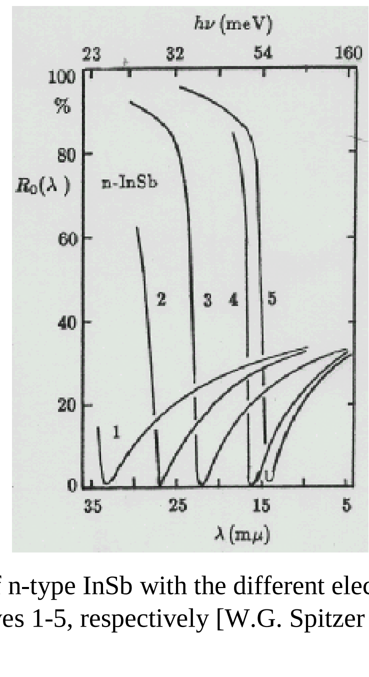

Figure 20 Reflection spectrum of n-type InSb with the different electron densities 3.5×10^{17}, 6.5×10^{17}, 1.2×10^{18}, 2.8×10^{18} and 4×10^{18} cm^{-3}, for curves 1-5, respectively [W.G. Spitzer and H.Y. Fan, Phys. Rev. 106, 882 (1957)].

The discussion of plasma in metals and semiconductors is quite similar to the discussion in the chapter above concerning the generation and absorption processes of free carriers in semiconductors. For the gas phase it should normally be more difficult to ionise atoms in order to generate a plasma as compared to a semiconductor. This could especially be a problem if an IR laser pulse is to be the generation mechanism for the plasma. However, the generation of a plasma in a gas could have some advantages as compared to the situation in the solid state, since permanent damage at very high irradiance levels is more likely to occur in a solid material as compared to a gas.

4.4 LASER DAMAGE THRESHOLDS

As pointed out above, laser damage thresholds and laser damage mechanisms are important issues in discussing laser protection devices for the infrared wavelength region. All of the self-activating protection principles are dependent on the incident intensity or the fluence of the radiation. This fact requires a location close to a focal plane or in an intermediate focus. Sometimes the activation levels for a certain protection device or material is close to the damage level. Methods and principles for laser damage studies are considered important in relation to studies of laser protection devices in the infrared wavelength region. Methods and principles for laser damage studies have been discussed in a previous report[25].

5 International activities

There are some comments that can be made concerning the combined political and military view on casualties. The home front is not likely to accept any dead and/or wounded soldiers in the modern warfare scenario with operations far from the home country. This is especially true when the outcome of the operations do not directly influence the national security of the home country. This is one important reason behind the massive development of laser and high power microwave countermeasures against missiles in Europe and America. There is also a parallel development of more conventional weapons to defeat missiles, e.g. an Australian effort on a multi-barrel gun where each barrel contains several projectiles. As a result, a number of laser systems against IR-missiles will be on the market during the next few decades. This in turn will increase the risk that our IR-seekers will be defeated by an opponent in the event of war or war-like conflicts. Within the scope of this report we therefore have to concentrate effort on protective devices against the laser threat.

The international agreement of 1996 on banning the use of military lasers with the purpose of causing permanent blindness to the unaided eye has created a more open attitude towards international sharing of information on sensor protection in the visible. Restrictions on the distribution of information in the mid-IR regime are more common and it is therefore difficult to present a good overview of international trends.

It is obvious, however, that the development of lasers for systems like NEMESIS has to be accompanied by corresponding efforts on sensor protection in the mid-IR-regime. Naturally no defence force would be likely to reveal national plans concerning whatever protective technique they plan to launch in their sensor systems.

The threat from carbon-dioxide lasers, in the far-IR band, may occasionally be neutralised by filters, since the CO_2-laser only delivers radiation at a rather narrow wavelength band. These filters are likely to be effective against jamming and against damage. The laser threat in the mid-IR-band will have less predictable wavelengths, and it will therefore be harder to specify a notch-filter that would effectively counter the threat. On top of the unpredictable wavelength scenario, we have a stronger short pulse threat since it is becoming feasible to utilise Q-switched lasers as pump sources for wavelength conversion equipment.

A particular area of interest to many military research organisations during the last decade is Mott transitions. In a Mott transition the internal electron-structure of a material is changed as a consequence of some influence from its surroundings. An example often cited is vanadium-dioxide which changes from a transparent, semi-conducting phase to a highly reflective, semi-metallic state at a threshold temperature.

6 Conclusions

The first priority as stated in chapter 3 is to protect detectors against damage from short laser pulses. There are three main demands on this protection:

A. High attenuation for harmful radiation

B. High transmission for non-harmful radiation

C. High transition speed between transmitting and attenuating states

The most promising protective principles for optical limiters described in chapter 4 seem to be:

1. Absorption due to free-carriers in semiconductors

2. Light induced phase transitions.

The information in chapter 4 indicates that these principles have a reasonable chance of fulfilling demands A and C. There is limited information available about transmissive properties and there is also an uncertainty about the damage threshold of the materials and possible devices.

We will aim at demonstrating one or both of these principles for protection in an IR-limiter in year 2003. Competing technologies that evolve until 2003 will of course also be considered.

The second and third priorities, as described in chapter 3, is protection of scanning seekers against jamming and to provide protection against closed loop interrogation of the seeker. Active protection is the only possible solution here since the limiting materials are not sensitive enough to attenuate jamming or interrogating radiation. The most attractive device concept to solve the second and third priority tasks would be frequency agile filters. Unfortunately there is no good concept idea available for the production of such a device today. Nevertheless we would like to pursue this area since the benefits of such devices would justify a high-risk research project.

We are aiming at developing knowledge about agile IR-filters to a level at which we will be able to propose a protective principle concept in year 2003. Optical shutters and SLMs is the second option in active protection. We will propose a protective principle based on shutters if we do not find any promising route to agile filters. Phase transitions may prove to be interesting in this respect too.

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