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Review and Prospects of Optical Countermeasures Technologies

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ABSTRACT

The paper reviews topics presented at past conferences on "Technologies for Optical Countermeasures", summarizes current optical countermeasures technologies, and illuminates technology trends which might be of interest in the future.

Keywords: optical countermeasures; directed infrared countermeasures; infrared lasers; laser effects; missile guidance

1. INTRODUCTION

Optical sensors observe our life everywhere, day and night. Some examples: neighbourhood watch, smart phone cameras; surveillance networks in cities, shopping malls, airports; autonomous vehicles may soon be on the streets capturing the roads and adjacent environments; bar code readers and cameras checking our purchases in grocery stores or our ID at gateways and border controls; security and defence related optical, infrared, and laser-based sensors providing information to police, counter-terrorism, or military forces. We will not be able to escape the fields of view or the illuminating light cones of optical sensors. An increasing number of citizens feel a need for optical countermeasures (OCM) to protect privacy and integrity in the public domain. In the defence arena optical countermeasures are a requirement for the survivability in a hostile environment.

The gamut of measures to counter optical sensors comprises a variety of techniques. The simplest one is a piece of tape to cover the aperture of a smart phone camera. Ingenious techniques are employed to protect documents against counterfeit. Combinations of sensors, bright decoys, and lasers are necessary to jam missile seekers heading towards civilian and military aircrafts.

In parallel to the development of countermeasures technologies the sensor engineers develop counter-countermeasures (CCM). There is a fruitful competition between the OCM and the CCM teams. A prominent example of non-technical CCM comes from the public domain: OCM technologies against law enforcing surveillance networks or security and safety related sensors (e. g. speed control sensors; very important: optical guidance sensors of autonomous vehicles) is already or will be regulated by law.

This paper reviews optical countermeasures against missiles that have been presented at SPIE's *Conference on Technologies for Optical Countermeasures* since the start in 2004. The majority of papers concentrated on methods, subsystems, and components related to this subject. We address the topic according to the following classification scheme:

- optical countermeasure systems, modelling, and simulation
- effects on sensors and non-lethal laser dazzling
- laser beam generation technologies
- laser beam steering and propagation
- optical components and materials
- supporting technologies and methods
- development trends

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2. MISSILE GUIDANCE

This section provides elementary information on missile guidance [1], a prerequisite for countering missile attacks effectively. Essentially, all guidance systems realize a closed-loop control system comprising a target tracker, a missile tracker, and a missile steering subsystem with a guidance computer and a command link. The location and the implementation of these subsystems distinguish the different types of missile guidance systems. We restrict ourselves to moving targets and to missiles which are commanded either to line-of-sight (LOS) trajectories or are guided by proportional navigation (PN). LOS guidance systems command the flight path of the missile in such a way that it always lies on the current LOS (or within a small basket around the LOS) between the location of the fire control sensors and the target. Examples are the different variants of command-to-line-of-sight (CLOS) and beam rider (BR) missiles. PN trajectories, on the other hand, are adopted by the majority of homing missiles such as man-portable air defence systems (MANPADS). The PN guidance law assumes that the rate of change of the tangent to the flight path is proportional to the rate of change of the line-of-sight to the target provided by an on-board target tracker.

CLOS guidance systems require the target tracker, the missile tracker, and the launch point to be in close vicinity. The axis of the missile tracker follows the axis of the target tracker. After the launch of the missile, the missile tracker detects any deviation of the flight path from the axis of the target tracker using a rear-facing beacon on the missile. The computer of the missile steering subsystem computes the required lateral acceleration to bring the missile back on track towards the target. The steering command is transmitted to the missile via a command link which could be a pair of wires, an optical fibre, a laser, or a radar beam. There are three groups of CLOS guidance systems depending on the way the missile is tracked: manually (MCLOS), semi-automatically (SACLOS), or automatically (ACLOS). In the case of MCLOS and SACLOS the target is tracked by a human operator, in the case of ACLOS also the target tracking is performed automatically.

BR guidance systems control the flight path of anti-tank guided weapons (ATGW) and of low level surface-to-air missiles (SAM). The target tracking is performed by a human operator similar to CLOS. The missile tracker is replaced by a laser beam which serves as an optical rail for the missile. A rearward looking laser receiver in the missile measures its lateral position within the beam. During the final period of the missile attack the laser beam axis and the target tracker axis are collinear and the missile spirals into the target. The major difference between the CLOS and BR guidance systems is the location of the guidance computer: it is located at the launcher for CLOS and inside the missile for BR.

There are two possibilities to counter a CLOS or BR missile attack: pre-emptive (proactive) CMs which prevent the launch of the missile, for example by detecting the target tracker and inhibiting lock-on before launch, and reactive CMs after missile launch, e. g. using platform manoeuvres to prevent the missile from hitting its target. Optical measures to counter CLOS and BR guided missiles must be applied to the optical sensors (human eye, detectors, and cameras) of the target and the missile trackers at the command post. Denying the attack using optical effectors against the optical devices on board of the missile seems to be ineffective as they are placed at the rear-facing side of the missile.

PN guidance is the dominant method to steer surface-to-air (SAM) and air-to-air (AAM) missiles into their targets. The target tracker and the guidance computer are both located inside the missile. Depending on the type of the target tracker (seeker) one distinguishes active, passive, and semi-active homing guidance. Active homing missiles use on-board radar (rarely laser) sensors to illuminate the target and to derive the lateral acceleration commands from the energy scattered off the target. Passive seekers sense the energy emitted (or sun light reflected) from the target. Semi-active seekers extract the homing information from radiation scattered off the target which is illuminated by a source located away from the missile. In all three cases an optical sensor may be a component of the target tracker inside the missile. Consequently, optical countermeasures systems on board of a jeopardized platform could be used to prevent a seeker from locking onto the target before launch or to steer the missile away after launch.

3. TECHNOLOGIES FOR OPTICAL COUNTERMEASURES CONFERENCES 2004-2018

The conference on *Technologies for Optical Countermeasures* started in 2004, initiated by Prof. David H. Titterton, at that time with the Defence Science and Technology Laboratory in UK [1]. Today, the triumvirate of Prof. Titterton, Prof. Mark A. Richardson (Cranfield University at the Defence Academy of the United Kingdom), and Dr. Robert J. Grasso (EOIR Technologies, USA) chair the conference supported by a Conference Programme Committee. The purpose of the conference is “to provide a technical forum for the discussion and dissemination of information on optical, electro-optical, and infrared technologies as applied to the countermeasure role in security and defence” as David Titterton and Mark Richardson wrote in their introduction to the fourth conference proceedings in 2007.

The locations of the conferences are chosen among major cities within Europe. Table 1 gives an overview of the conference venues and the corresponding proceedings number since 2004.

Table 1 Overview of the years, proceeding numbers, and venues of the Conferences on Technologies for Optical Countermeasures

NO	PROC	YEAR	LOCATION
I	5615	2004	London
II	5989	2005	Bruges
III	6397	2006	Stockholm
IV	6738	2007	Florence
V	7115	2008	Cardiff
VI	7483	2009	Berlin
VII	7836	2010	Toulouse
VIII	8187	2011	Prague
IX	8543	2012	Edinburgh
X	8898	2013	Dresden
XI	9251	2014	Amsterdam
XII	9650	2015	Toulouse
XIII	9989	2016	Edinburgh
XIV	10435	2017	Warsaw
XV	10797	2018	Berlin

The topics presented during the conferences cover OCM system aspects, simulation, modelling, generation and propagation of laser beams, laser effects on sensors, and supporting technologies – to name a few. A coarse classification of the presentations together with the number of papers distributed over the conferences until today as documented in the proceedings (I to XV) is given in Table 2. The corresponding Figure 1 depicts the total number of papers in each category.

Table 2 Summarizing classification of topics covered by the Conferences on Technologies for Optical Countermeasures

TOPIC	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV
Analysis, Modelling & Simulation	4	3	4	1	3	5		5	8	2	3		1	1	
CM Systems & Applications	7	2		1	1	2	2	1	1	1	2	1	2	2	1
Effects & Non-Lethal Laser Dazzling			2	3	1			1		3	2		2		8
Laser Beam Generation Technologies	4	7	5	11	6	12	15	3	8	6	7	2	3	5	10
Laser Beam Steering & Propagation	2		4	2	6	1	4	1	1			3	2	4	
Optical Components & Materials		1	1		4			1		1				1	
Reviews & General Issues	1			4		1			1		1		2		2
Supporting Technologies & Methods				1	1	5		4	2	3		1	6	2	9

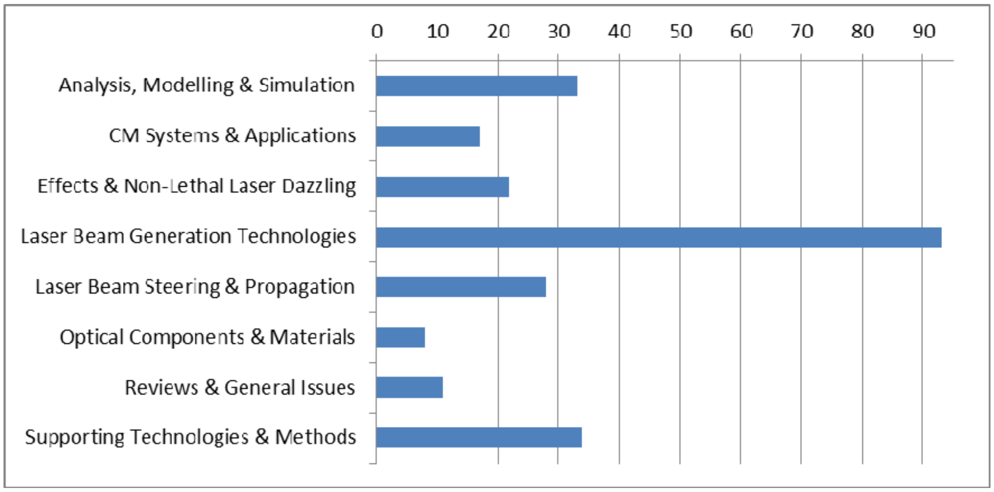

Figure 1 Number of papers in each category

The figure shows clearly that the majority of the roughly 250 presentations in 15 years cover laser technologies (pump lasers, optical parametric oscillators, quantum cascade lasers, and other infrared semiconductor lasers), and related components. Beam steering and propagation, analysis/modelling/simulation of subsystem and system aspects, and supporting technologies (threat detection, discrimination, and tracking) come next. These papers have been a valuable source of information not only for the experts, reflecting the status and progress of research in academia and industry, primarily on OCM against MANPADS. A couple of talks on CM applications, effects on sensors and humans (laser safety, laser dazzling), and reviews of technology trends, projects, and programs complete the comprehensive collection of papers on Technologies for Optical Countermeasures.

In addition to papers presented to an audience, the conference chairs established in 2013 a panel discussion session which offers the participants a forum to discuss several relevant topics such as Closed-Loop Directed Infrared Countermeasures (DIRCM-CL) or the relation between Directed Energy Weapons (DEW) and Infrared Countermeasures (IRCM). This moderated forum supplements the standard presentation format and encourages the participants to express their opinions and thoughts in front of a wider audience than that available in the coffee breaks between the sessions.

4. OPTICAL COUNTERMEASURE SYSTEMS

The fundamental function of an OCM system is to use an intense optical source to prevent an operator or a target tracker from performing its intended task (e. g. observation, aim point selection, or tracking). Maximizing the radiant intensity (W/sr) of the light source in the short (2 - 2.5 µm) and mid-wave (3.4 - 5 µm) infrared atmospheric transmission windows was a major driver for the evolution of OCM systems against MANPADS [2,3]. In general, the electrical input power to the source is limited. Thus, maximizing the spectral radiant intensity must be achieved by maximizing the energy conversion efficiency of the electro-optical subsystem, by concentrating the optical power into the required spectral bands, and by reducing the angular divergence of the light beam. These requirements fit very well to the characteristics of the laser. The use of a laser transforms an infrared countermeasure (IRCM) into a directed infrared countermeasure (DIRCM) system. The DIRCM architecture requires a beam director with high target tracking accuracy and high pointing stability to illuminate the moving target.

Figure 2 describes the basic operating principles of a DIRCM system mounted on an airborne platform. A missile approach warning sensor (suite) observes the volume around the air vehicle, acquires and discriminates possible target missiles, and establishes tracks. The prioritized target is handed over to the beam director for further tracking and pointing of the laser beam towards the seeker. A jamming sequence, essentially an on-off-keying of the power of the laser beam, is transmitted and the response of the target missile is monitored to assess the effectiveness of the countermeasure. Successful jamming drives the illuminated missile away from its target and allows the DIRCM system to point the beam

Figure 2 Basic operating principles of a DIRCM system (source: Diehl Defence)

director to another missile. DIRCM is currently the most advanced technique that is being deployed on new aircrafts like the A400M [4] or retrofit onto older ones to counter the effectors (missiles) of MANPADS.

The ancestor of the DIRCM is the omnidirectional IRCM system [5]. Early devices used fuel or electrically heated rods to generate the IR energy and a pair of rotating slotted cylinders to modulate the emission. These systems suffered from low jamming radiant intensity which could hardly overcome the signature of the platform to be protected. The next IRCM generations employed arc and discharge lamps in order to increase the spectral power density of the jamming signal. The arrival of missile warning sensors (MWS) which provide directional information about the approaching missile with high angular accuracy paved the way for directional IRCM. Based on the angular information the infrared lamp power is concentrated into a small solid angle around the direction indicated by the MWS. The AN/AAQ-24 NEMESIS was among the first DIRCM systems in production [6]. Later on, the lamp was replaced by the Viper laser [7].

A different way to counter infrared-guided surface-to-air and air-to-air missiles is the use of pyrotechnic decoys such as flares. A flare provides a source of IR energy within the field of view of the seeker which is usually much brighter than the signature of the target platform. The flare is dispensed from the platform and moves away from it aiming at distracting the missile away from its primary target. Sequences of flares can be emitted to ensure confusion of the target-tracking system in the approaching missile, or salvoes of missiles [2]. In addition to flares, ground vehicles and ships use obscurants (separately or in combination with flares) to defeat a missile attack [8,9,10].

(D)IRCM and infrared flares are not effective against CLOS and BR guided missiles (or rocket propelled grenades, RPGs) because these threats do not have any optical sensors facing the target on board. These weapon systems involve a human operator to acquire and track the target during missile flight using either an optical or a thermal sight. As analysed in Ref. [11], there are three possibilities to disrupt the visual task of an operator with optical countermeasures such as flares, lasers or a combination of both: by an intense flash of light, by an annoying light flicker or by a glare source. In all cases, the rules of engagement require that the Protocol IV of the Geneva Convention [12] will be respected.

In the context of CLOS and BR weapon systems the interest in proactive/pre-emptive optical countermeasures was intensified recently. Conventional missile warning sensors are looking for flashes indicating the launch of a missile. Pre-emptive OCM emphasizes the importance of detecting and analysing additional signatures indicating the preparation of a missile launch, radiation emitted from a suspicious site, retro-reflection off optical sights, and others [13,14].

The development of effective OCM techniques and their implementation into a system to protect a platform requires the analysis of the platform's susceptibility of being engaged by a missile in a hostile environment, accurate modelling of the behaviour of a launched missile, the evaluation of target detection and tracking algorithms, and the analysis of the survivability of the platform once a damage has occurred. Several conference papers and references therein provide unclassified data and models based on elementary physics as a starting point for further analysis [13,14,15,16,17,18].

Illegal trading of light weapons poses an international security problem [19]. Missile systems, especially MANPADS, operable by a single user or a small group are readily available on the black market with possible grave consequences to a highly mobile modern society: missile attacks are not only a problem for military aircrafts, but also civil airliners may be jeopardized by these weapons. The footprint for attacking large commercial aircrafts during take-off, ascent, and landing is large. The on-board defence technologies against MANPADS developed for military aircraft cannot be migrated to commercial aircrafts without significant changes, e. g. in the architecture of the defensive aids system [20].

5. EFFECTS AND NON-LETHAL LASER DAZZLING

How does an optical countermeasure act onto an optical sensor? In a first reaction, one assumes that the answers to this question belong to the type of information that cannot be shared between the participants of an international conference. Luckily, the physics of optical countermeasures is the same in every laboratory and on any test field worldwide. Consequently, general physical aspects are available in the proceedings of the conference. In general, there are three possibilities to disrupt the functioning of any optical sensor: (i) jamming of the signal processing; (ii) preventing the conversion of information from the optical onto the electronic carrier by dazzling; (iii) damage of electro-optical components. The required optical power that must be generated by the light source of the OCM system increases from jamming over dazzling to damage and is a function of the sensor technology and of the wavelength.

The seekers of the first and second generation MANPADS [2] can be readily jammed by IRCM and DIRCM systems or irritated by using flares [21]. The next generations of seekers transitioned from temporal signal processing of spatially unresolved targets (hot spot trackers) to spatial signal processing using a small number of detectors (pseudo-imaging), and, later on, to full frame image processing of resolved targets. Correspondingly, OCM systems must adopt their countermeasure techniques to these new challenges. The research towards new OCM techniques was supported by the NATO-SCI-139 group who built an unclassified infrared imaging surrogate seeker (ISS) as an evaluation tool [22]. The ISS was used by the group members to gain insight into the dazzling of focal plane arrays, i. e. preventing the seeker from converting the information from the optical onto the electronic carrier [23]. Figure 3 depicts a photograph of the ISS and unclassified results of the dazzling experiments.

The problem of OCM against imaging seekers is still under discussion [24] and may not be settled within the near future. There have been ideas to use femtosecond (fs) lasers to create active decoys against (imaging) IR homing missiles or to damage the seeker electronics [25,26,27]. Fs-laser beams exhibit a very high power density and form plasma filaments

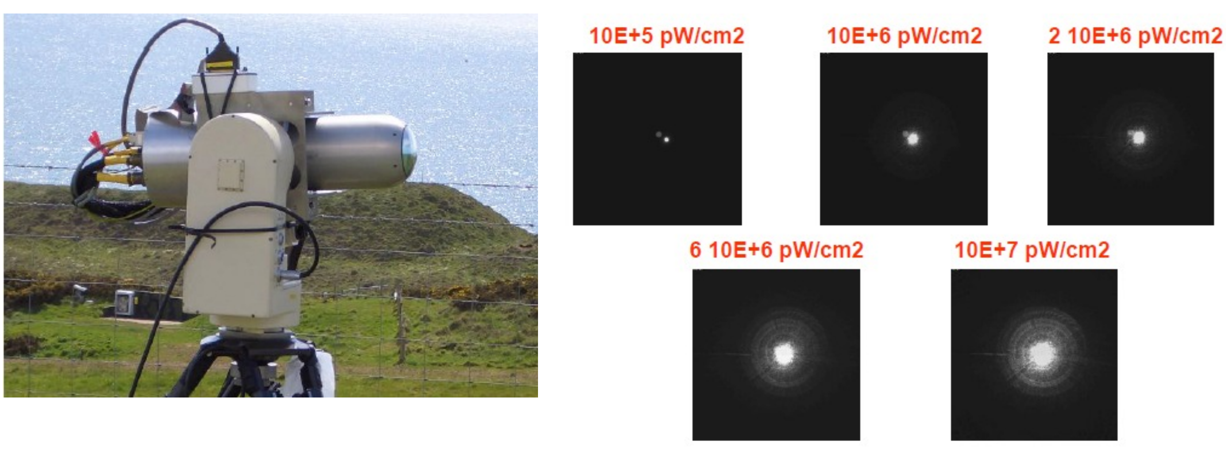

Figure 3 Imaging surrogate seeker (ISS) built by the NATO-SCI-139 group for the evaluation of OCM against imaging IR seekers; left: photo of the ISS on a tracking platform during field tests; right: impact of various CW laser irradiance levels on the ISS image (source: Ref. 22)

on their way through the atmosphere. Why not create artificial flairs in air by using plasma effects and divert guided missiles from their interception course by projecting moving hot spots or even 3D false targets? The analyses explained in Ref. [27] showed that the application of femtosecond laser beams for the irritation of missile seeker heads is not in any way promising, neither via white-light generation with ultra-short laser pulses nor via glowing plasmas. The generated light intensity is too low to successfully compete with the signal of a typical platform. The most promising countermeasure realized with femtosecond laser beams seems to be related to the damage of opto-electronic components of the seeker system. Damaging components is also a route explored by the application of out-of-band directed energy weapons (DEW) [28]. In this context the main questions are: Is it possible to generate sufficient radiant intensity on board of an airborne platform to damage seeker components? Can the laser beam be pointed with sufficient accuracy towards the seeker in order to deliver the required power-in-the-bucket? How is a high power laser beam transmitted through the atmosphere complying with physical limitations and respecting non-technical (e. g. airport safety) regulations?

Countering CLOS and BR guided missiles requires to deny the target acquisition or to interrupt the target tracking processes. Dazzling of the human operator is a feasible OCM technique, restricted by the application of the Geneva protocol. Likewise, the electro-optical tracking equipment may be dazzled. A couple of papers (see for example [29,30]) described these techniques, the system requirements, and the "escalation of force" methodology to cope with the safety issues associated with the application of potentially blinding laser beams.

6. LASER BEAM GENERATION

A laser beam is an ideal effector for an OCM system: The optical energy is generated within a narrow spectral range and with a beam quality which allows for the concentration of the energy within a small solid angle providing a high spectral radiant intensity (W/µm/sr). A simple order of magnitude calculation illustrates this fact: A MTV flare radiates as a black body of 2000 K approximately 25 kW over 3 sec omnidirectional in the 3-5 µm spectral band [11]. An infrared laser releases photons (quasi-) continuously with 1 W output power in the band 3.9 to 4.0 µm and with a full ($1/e^2$) divergence of 3.7 mrad after the beam director. The mean radiant intensities of both sources in the spectral band 3.9 - 4 µm, where the atmospheric transmittance is high and IR guided MANPADS are sensitive, are 94 W/sr for the flare and 93 kW/sr for the laser, i. e. the radiant intensity of the laser is three orders of magnitude higher than that of the flare. The price to pay for this radiometric advantage is an increased architectural complexity requiring a missile warning sensor with high angular accuracy and a beam director which collimates and points the laser beam.

Generating a laser beam with 1 W of infrared optical power was a challenge in the early days of the deployment of DIRCM systems. There were a couple of technologies to choose from (see Figure 4, adapted from Ref. 38). In the very first conference in the year 2004 the technology bricks to realize a high power infrared laser were presented: fibre-pumped optical parametric oscillators (OPO) [30] and quantum cascade lasers (QCL) [31]. In addition, the requirements

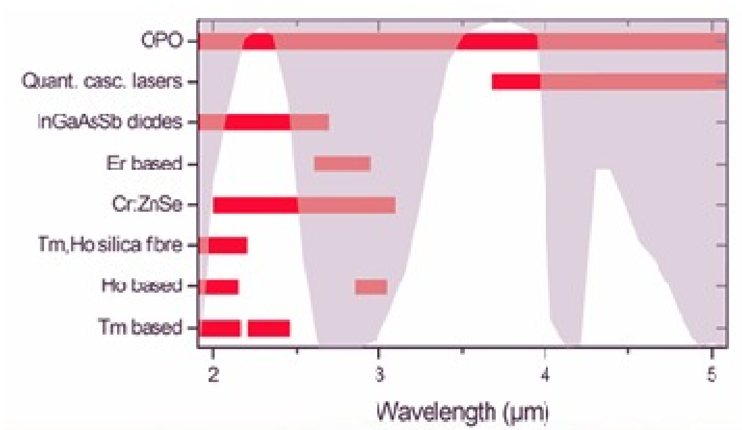

Figure 4 Spectral coverage of various advanced IR laser technologies (adapted from Ref. 38)

for laser devices used in countermeasure applications were summarized [32]. In 2012 QCLs were declared ready for IRCM applications [33] and their industrialization was demonstrated [34]. In-between a semiconductor mid-infrared laser source combining QCLs for the spectral range 3-5 µm and optically pumped semiconductor disk lasers (OPSL) for the 2-2.5 µm transmission window, both operating at room temperature, was demonstrated in field tests [35]. In parallel compact high power 2 µm fibre lasers and mid-infrared OPO sources for OCM were developed and tested in measurement campaigns (e. g. [36,37]). Since then, improvements in both technologies (semiconductor laser and OPO) have been reported.

As mentioned above, a multitude of papers from academia and industry were presented on the subject of infrared laser sources for optical countermeasures. Technologies related to OPO systems (NIR laser diodes, fibre lasers, Q-switches, wavelength conversion materials) and to infrared semiconductor lasers (diodes, OPSL, QCL) were discussed, architectures and design considerations have been outlined, and performance, system and industrialization issues were highlighted. Ref. [39] compares different laser architectures and addresses issues relevant for the design and manufacture for the military environment. The comparison of the OPO and semiconductor technologies in Ref. [39] refers to the state of the art in the year 2009. Especially the semiconductor lasers (OPSL and QCL) made an immense progress since 2009, e.g. with room temperature power levels in excess of 1 W for the single emitter.

Semiconductor lasers possess an inherent advantage compared to optical parametric oscillators because of the direct conversion of electrical into infrared optical energy without additional conversion units. This is suggestively illustrated in Figure 5 taken from Ref. [34]. The QCL module requires only an electrical input current (like a light bulb) to emit infrared photons. The OPO comprises a sequence of subsystems each of which requires skilled people for assembly and test. The parametric generation of infrared radiation is a complex process (many components, different physical processes). Nevertheless, infrared OPO-based light sources are currently industrialized and fielded in DIRCM systems.

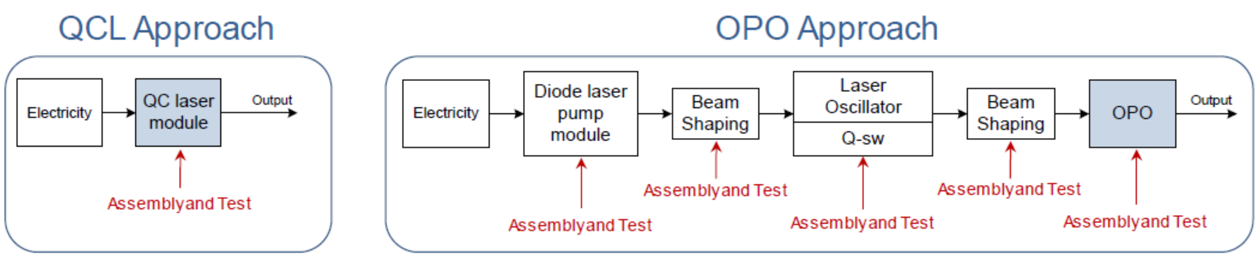

Figure 5 Comparison of technical approaches between QCL and OPO illustrate the inherent advantages in reliability and cost (source: Ref. 34)

The mastering of the technologies to generate infrared photons is essential for building an OCM system. Yet, the photon generator is only a part of the laser system. The other components are the power supply (comprising electronic components and optical pump diodes, if necessary), the thermal management subsystem, and the command and control electronics [40]. The engineering of these subsystems is equally important as they account for roughly 80% of the total power budget and a large portion of the size, weight, and costs of the laser source.

7. LASER BEAM STEERING AND PROPAGATION

Pointing a laser beam into a desired direction with a required angular divergence involves a beam director (turret). The optical system of the turret also comprises the optical path of the target tracker which generates the directional information. The size of the turret depends on the requirements for pointing and tracking, especially on the angular divergence and the quality of the multi-spectral laser beam. Early systems used separate apertures for the tracker and the laser beam. Current compact turrets realize a common aperture for both, the transmitter and the receiver optical paths [41].

The turret uses gimballed optical elements to compensate for platform motions and low frequency vibrations with moderate accuracy and speed. A beam steering device is needed if fine pointing and stabilization of the line-of-sight towards the missile seeker is required. In general, beam steering is accomplished by imposing a linear phase retardation profile across the aperture of the laser beam. The slope of the corresponding wavefront ramp determines the steering angle:

large steering angles correspond to large slopes and vice versa. Several technologies are available to realize this function, e. g. Risley prisms, micro-opto-electro-mechanical elements (MOEMS), or optical phased arrays [42].

High frequency disturbances may be introduced into the laser beam path by aero-optical effects such as aircraft's boundary layers, aircraft's wakes or jet engine plumes [43,44]. The fluctuation of the refractive index inside these turbulent structures causes beam wander, beam broadening, and beam scintillations. In most cases, these aero-optical disturbances in the vicinity of an aircraft are larger than those induced by the atmospheric turbulence along the beam path between the aircraft and the missile [45]. Beam broadening and beam wander reduce the irradiance of the laser beam in the seeker's aperture while beam scintillation may reduce the effectiveness of the jamming signal (see Figure 6, reproduced from Ref. 45). Scintillation could be a limiting factor for the synthesis of jamming codes in future closed-loop DIRCM systems. Aero-optical effects together with beam obscuration by mechanical aircraft structures influence the choice of the locations for the installation of DIRCM turrets.

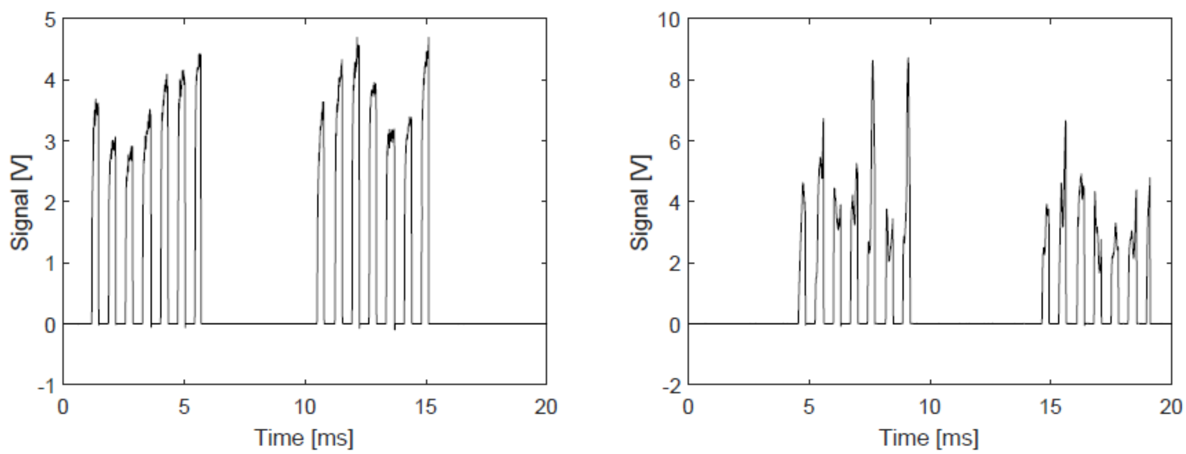

Figure 6 Example radiometer recording of "fake" jam code from DIRCM system. The left image is with engines off and the right with engines on (source: Ref. 45)

The propagation path from the aircraft through the atmosphere to the missile's seeker affects the laser beam and the passive tracking signal via absorption, scattering, refraction, and turbulence [46]. The net effect of the atmospheric influence is a reduction in transferred optical energy (which translates into a reduction of range) and a loss of information which may result in increased tracking and pointing errors. As mentioned above, the impact of the atmospheric path turbulence on the laser beam and its temporal modulation is smaller than that of the aero-optics in the vicinity of the platform. This is true for a short path of a few kilometres length joining an airborne platform with a surface-to-air missile.

8. OPTICAL COMPONENTS AND MATERIALS

Passive optical components are used to realize the optical functions of the OCM system: (i) collection of the optical radiation carrying the information about the (apparent) motion of the line-of-sight to the target (e.g. missile, command post) and projection of the collected radiation onto a detector plane; (ii) formation and combination of beams of photons inside the light source and guidance of the beams from the source to the emitting aperture(s); (iii) control of the proper alignment of the receiver and transmitter optical axes. The set of optical components include the classical arsenal such as lenses, mirrors, wedges, prisms, retro-reflectors, as well as multilayer dielectric coatings for filtering and spectral multiplexing, anisotropic crystals as frequency converters or as wave plates, non-imaging optics in optical pumping units or as optical fibres. The sizes of the optical elements range from micrometres (e.g. passive fibres) to millimetres (e.g. collimation optics for QCL) up to centimetres near the exit aperture. Depending on the spectral range (NIR for dazzling the operators of CLOS guided missiles, SWIR and MWIR for MANPADS) materials in use are glasses, semiconductors and amorphous thin film structures.

The OCM applications do not call for special requirements for the optical components and materials. The conference proceedings include a couple of informative papers and reviews about dual-use bimorph mirrors [47], micro-structured optical fibres [48], non-linear optical materials [49], or infrared fibres [50].

9. SUPPORTING TECHNOLOGIES AND METHODS

Supporting technologies and methods comprise all those topics not directly related to optical beam generation, beam pointing, beam steering and propagation, or target effects. They provide additional functions and features to an OCM system: some techniques are essential to ensure proper system performance such as the detection of dim target [51] or tracking sensors [52], some methods provide new functionalities to the system using laser-based sensors [53], e. g. for time-of-flight profiling [54], laser detection and ranging [55] or detection of polarization anomalies [56]. Field trials [22,41,57], IRCM spectral signature measurements [58], or laser safety analyses for DIRCM systems [59] are further examples of supporting activities.

10. CONCLUSION AND DEVELOPMENT TRENDS

The 15 conferences on Technologies for Optical Countermeasures provided a valuable forum for the exchange of results and new ideas among academic researchers, industry and governmental experts. The focus of the conferences quickly settled onto laser research for airborne DIRCM systems against MANPADS and related laser beam propagation issues. These important topics were partly driven by NATO, European, and national programmes. The talks presented up-to-date unclassified information. Looking ahead, new applications of OCM to increase the survivability of fast unmanned aircraft, ground and sea platforms using radiation in the atmospheric transmission bands ranging from UV up to LWIR will emerge.

The panel discussions, which were established as brain storming sessions accompanying the conferences, pointed out some of the routes that may be followed in future research programmes. Here are three questions looking for answers:

- What are the factors limiting the ability of closed-loop DIRCM systems to analyse the laser radiation scattered off seeker heads and how do these factors affect the synthesis of jamming codes in real-time?
- How do cost-effective architectures look like that merge directed countermeasure systems and directed energy weapons into a single laser effector system that can counter any threat regardless of its type (so-called threat agnostic countermeasure [60])?
- Which new source and modulation technologies have to be developed to jump "back to the future" and to keep, restore, or install IRCM systems on small platforms, thus eliminating the need for accurate but costly missile warner and beam directors?

The succeeding lines summarize additional research topics that may generate interest in upcoming conferences.

Optical countermeasure systems

OCM systems are part of a platform's electronic warfare (EW) equipment. Early EW systems served as "penetration aids" by supressing the enemy's ability to detect and attack the platform, thus aiding the delivery of payloads. Today, OCM systems belong to the "Aircraft Survivability Equipment" [60]. The future directions of OCM technologies research are derived from the top level requirement to provide integrated solutions capable of net-centric operations and digital interoperability. A magic formula to reduce size, weight, power, and cost (SWaP-C) is multi-functionality. An example, taken from Ref. [61], is shown in Figure 7: distributed DIRCM using a multi-functional laser system. The centralized high power laser is switched into several fibre delivery channels providing radiation to the turret "under attack".

Figure 7 The distributed DIRCM concept; left: before implementation; right: after implementation; yellow boxes: lasers; green circles: frequency conversion sources; red lines: fibre delivery system (source: Ref. 61)

In addition to performing the countermeasure function, the distributed apertures could be used for illumination, active imaging, range finding and profiling, designation/targeting, or marking. In the spirit of multi-functionality, a distributed aperture missile warner could execute several functions along with missile approach warning, namely detecting laser irradiation (beam rider attack), indicating hostile fire, or supporting the situational awareness of the platform [60].

Two new respectively revitalised countermeasure concepts are: pro-active and pre-emptive OCM [60]. Both countermeasure methods aim at denying the launch of a missile against a platform. In pro-active OCM, the threat is detected while the launch of the missile is prepared; pre-emptive OCM prevents the missile's seeker to lock on to the target before launch.

Laser beam generation technologies, propagation, and target effects

New light sources such as femtosecond lasers and super-continuum sources introduce new CM capabilities. Femtosecond lasers provide very high power levels which may induce new effects in focal plane arrays to be explored. A super-continuum source emits a very wide wavelength spectrum up to white light. This seems to be ideal for dazzling CCD and CMOS cameras. To be useful against infrared guided missiles the optical power spectral density should shifted into the infrared transmission windows of the atmosphere, ideally without generating useless optical energy in-between.

Concerning the multi-functional laser source, the fundamental technologies are known. Nevertheless, realizing such a source and integrating it into different platforms is a formidable engineering task. The functional architecture should be sufficiently open to incorporate new features not yet known in detail. The delivery system shall be scalable to support specific platform and mission needs.

A major unsolved problem in OCM against missiles is how to disturb the multi-spectral imaging seeker heads of the fourth generation and beyond. Multispectral focal plane arrays comprise a multitude of detectors in several spectral bands. At long ranges the platform under attack is not being resolved and every OCM source emerging from the platform is imaged onto a single pixel or a small group of pixels. Simply saturating or destroying that pixel is of no use. A fancy idea is to use a swarm of small UAVs to escort a high-value platform. The UAVs could be equipped with powerful QCLs and laser diodes to create a spatially extended target-like signature which attracts the attention of the imaging seeker or disturbs the image processing algorithms. The video of the *2018 Guinness World Records - Dances of 1374 Drones* [62] visualizes the essentials of this idea.

Optical components, materials, and supporting technologies

New ideas need new components and supporting technologies. Distributed apertures will be structurally integrated into the airframe of the platform. Freeform windows and aberrations compensating optics will be required, exhibiting large apertures and wide field of views. One step further away may be the use of digital optics to compensate the aberrations in the optical path of a multi-functional missile warner using image processing algorithms.

The beam forming optics of a multi-functional laser may ask for high power resistant phase modulators to null the wavefront aberrations introduced by the freeform window. Non-mechanical beam steering and switching is an old idea still waiting to be engineered into products. High peak power fibres for power delivery and in-fibre non-linear frequency conversion or super-continuum generation in harsh environments is on the wish list as well as low-loss infrared fibres for combining multiple QCL beams.

Large format, multi-spectral uncooled, at least high operating temperature (HOT), focal plane arrays with adequate sensitivity could make a contribution to the reduction of SWaP-C. Small arrays of fast uncooled detectors would be welcome for laser sensing and active tracking. Algorithms capable of extracting information about the optical sensor of the target (closed-loop CM) from the backscattered countermeasure laser beam or about the irradiation of the target (target-in-the-loop) under conditions of severe aero-optical or atmospheric turbulence would complement the research into new hardware subsystems and components.

The information capacity of the optical sensors to be countered is increasing dramatically (multi-spectral 3D imaging sensors). The modelling and simulation environment for the evaluation of countermeasure effectiveness should be updated continuously with accurate, high-fidelity models and suitable data handling capability (Big Data) in order to simulate a multitude of CM engagements within a wide variety of scenarios.

REFERENCES

[1] J. F.Rouse, "Guided Weapons," 4. Edition, Brassey's, London (2000)
[2] M. A. Richardson, "The anatomy of the MANPAD,", Proc. SPIE 6738 (2007)
[3] D. H. Titterton, "A review of the development of optical countermeasures," Proc. SPIE 5615 (2004)
[4] http://www.bundeswehr-journal.de/2016/airbus-a400m-selbstschutz-mit-dass-und-dircm/
[5] R. Grasso, "Source technology as the foundation for modern IRCM," Proc. SPIE 7836 (2010)
[6] https://www.northropgrumman.com/Capabilities/DIRCM/Pages/default.aspx
[7] https://www.northropgrumman.com/Capabilities/ViperMidIRLaser/Documents/viper.pdf
[8] R. Walmsley, B. Butters, R. Ayling, M. Richardson, "Modelling of countermeasures for AFV protection against IR SACLOS systems," Proc. SPIE 5989 (2005)
[9] B. Butters, E. Nicholls, R. Walmsley, R. Ayling, "Infrared decoy and obscurant modelling and simulation for ship protection," Proc. SPIE 8187 (2011)
[10] H.M.A. Schleijpen, M. Degache, H. Veerman, R. van Sweeden, B. Devecchi, „Modelling infrared signatures of ships and decoys for countermeasures effectiveness studies," Proc. SPIE 8543 (2012)
[11] A. Toet, K.W. Benoist, J.N.J. van Lingen, and H.M.A. Schleijpen, "Optical countermeasures against CLOS weapon systems," Proc. SPIE 8898 (2013)
[12] United Nations, "Protocol on blinding laser weapons (Protocol IV to the 1980 United Nations Convention on Certain Conventional Weapons)", United Nations, Vienna, Austria, 1995
[13] O. Steinvall, "Potential of preemptive DIRCM systems," Proc. SPIE 9650 (2015)
[14] L. Sjöqvist, L. Allard, M. Pettersson, P. Börjesson, N. Lidskog, J. Bodin, A. Widen, H. Persson, J. Fredroksson, S. Edström, "Optics detection and laser countermeasures on a combat vehicle," Proc. SPIE 9989 (2016)
[15] H. Bekman, J.C. van den Heuvel, F.J.M van Putten, H.M.A. Schleijpen, "Development of a mid-infrared laser for study of infrared countermeasures techniques," Proc. SPIE 5615 (2004)
[16] C.J. Willers, M.S. Willers," Simulating the DIRCM engagement: component and system level performance," Proc. SPIE 8543 (2012)
[17] C.J. Willers, M.S. Willers, A. de Waal, "Aircraft vulnerability analysis by modelling and simulation," Proc. SPIE 9251 (2014)
[18] I. James, "Physics based performance model of a UV missile seeker," PROC. SPIE 10435 (2017)
[19] T.E. Lizotte, O.P. Ohar, "Tracking illicit small arms trafficking: implementation of International Firearm Microstamping (IFM) to small arms and light weapons imports and exports," Proc. SPIE 7483 (2009)
[20] H.D. Tholl, J.F. Vergnolle, "CASAM - An European R&T project for the protection of commercial aircrafts in flight," Proc. SPIE Vol. 7115 (2008)
[21] J. Jackman, M. Richardson, B. Butters, R. Walmsley, "Modelling a man-portable air-defence (MANPADS) system with a conical scan two-colour infrared (IR) seeker," Proc. SPIE 8187 (2011)
[22] H.M.A. Schleijpen, S.R. Carpenter, B. Mellier, A. Dimmeler, „Imaging seeker surrogate for IRCM evaluation," Proc. SPIE 6397 (2006)
[23] H.M.A. Schleijpen, A. Dimmeler, B. Eberle, J.C. van den Heuvel, A.L. Mieremet, H. Bekman, B. Mellier „Laser dazzling of focal plane array cameras," Proc. SPIE 6738 (2007)
[24] W.D. Caplan, "Requirements for laser countermeasures against imaging seekers," Proc. SPIE 9251 (2014)
[25] G. Mechain, A. Mysyrowitz, M. Depiesse, M. Pellet, "A virtual antenna produced in air by intense femtosecond laser pulses," Proc. SPIE 5989 (2005)

[26] E. Marquis, J.P. Pocholle, "Novel applications in femtosecond lasers in missile countermeasures," Proc. SPIE 5989 (2005)

[27] G.C. Franssen, H.M.A. Schleijpen, J.C. van den Heuvel, H. Bürsing, B. Eberle, D. Walter, "Femtosecond lasers for countermeasure applications, " Proc. SPIE 7483 (2009)

[28] D.C. Shannon, "Non-lethal laser dazzling as a personnel countermeasure," Proc. SPIE 8898 (2013)

[29] A. Durecu, O. Vasseur, P. Bourdon, "Quantitative assessment of laser-dazzling effects on a CCD-camera through pattern-recognition-algorithms performance measurements," Proc. SPIE 6738 (2007)

[30] E.J. O'Driscoll, M.A. Watson, "Design and construction of a photonic-fibre-pumped OPO for active sensor systems," Proc. SPIE 5615 (2004)

[31] C. Sirtori, X. Marcadet, M. Garcia, A.N. Baranov, R. Teissier, D. Barate, A. Vicet, C.L. Alibert, J.W. Cockburn, D. Revin, "The quantum cascade laser: the semiconductor solution for lasers in the 3-5µm wavelength region," Proc. SPIE 5615 (2004)

[32] D. H. Titterton, "Requirements for laser devices used in countermeasure applications" Proc. SPIE 5989 (2004)

[33] M. Razeghi, "Quantum cascade lasers ready for IRCM applications," Proc. SPIE 8543 (2012)

[34] T. Day, M. Pushkarsky, D. Caffey, K. Cecchetti, R. Arp, A. Whitmore, M. Henson, E.B. Takeuchi, "Quantum cascade lasers for defence and security", Proc. SPIE 8898 (2013)

[35] H.D. Tholl, J. Wagner, M. Rattunde, S. Hugger, F. Fuchs, "Mid-infrared semiconductor lasers for power projection and sensing," Proc. SPIE 7836 (2010)

[36] W. Lippert, "Progress with OPO-based systems for mid-IR generation," Proc. SPIE 8187 (2011)

[37] C. Kieleck, A. Hildebrandt, M. Schellhorn, G. Stoeppler, M. Eichhorn, "Compact high-power/high-energy 2 µm and mid-infrared laser sources for OCM," Proc. SPIE 8898 (2013)

[38] A. Godard, M. Lefebvre, S.A.S. Hassani, P. Galtier, "Development of a compact laser source for airborne countermeasures," Proc. SPIE 6738 (2007)

[39] A. Sijan, "Development of military lasers for optical countermeasures in the mid-IR," Proc. SPIE 7483 (2009)

[40] I. Elder, "Performance requirements for countermeasure lasers," Proc. SPIE 7836 (2010)

[41] S. Chapman, I. Wildgoose, E. McDonald, S. Duncan, "Field testing the next generation pointer/tracker for IRCM," Proc. SPIE 7115 (2008)

[42] H.D. Tholl, "Novel laser beam steering techniques," Proc. SPIE 6397 (2006)

[43] L. Sjöqvist, "Laser beam propagation in jet engine plume environments: a review," Proc. SPIE 7115 (2008)

[44] O. Pade, "Modeling aero optics effects in jets," Proc. SPIE 7115 (2008)

[45] M. Henriksson, C. Eisele, D. Seiffer, L. Sjöqvist, F. Togna, M.-T. Velluet, „Airborne platform effects on lasers and warning sensors," Proc. SPIE 10435 (2017)

[46] A.M.J. van Eijk, K. Stein, "Atmospheric and laser propagation," Proc. SPIE 10435 (2017)

[47] M.S. Griffith, L.C. Laycock, J.M. Bagshaw, D. Roew, „Dual-use bimorph deformable mirrors," Proc. SPIE 5989 (2005)

[48] E.J. O'Driscoll, M.A. Watson, T. Delmonte, M.N. Petrovich, X. Feng, J.C. Flanagan, J.R. Hayes, D.J. Richardson, "Microstructured fibres: a positive impact on defence technology?," Proc. SPIE 6397 (2006)

[49] P.D. Mason, L.F. Michaille, "Review of the development of nonlinear materials for mid-IR generation," Proc. SPIE 7115 (2008)

[50] D.L. Rhonehouse, J. Zong, D. Nguyen, R. Thapa, K. Wiersma, C. Smith, A. Chavez-Pirson, "Low loss, wide transparency, robust tellurite glass fibers for mid-IR (2-5 µm) applications," Proc. SPIE 8898 (2013)

[51] G.M. Mirsky, M. Woods, R.J. Grasso, "Detection of dim targets in multiple environments," Proc. SPIE 8898 (2013)

[52] J. Pawluczyk, A. Sosna, D. Wojnowski, A. Koźniewski, M. Romanis, W. Gawron, J. Piotrowski, "Higher operation temperature quadrant photon detectors of 2-11 µm wavelength radiation with large photosensitive areas," Proc. SPIE 10435 (2017)

[53] O. Steinvall, "Review of laser sensing devices and systems," Proc. SPIE 5989 (2005)

[54] L. Sjöqvist, M. Hendriksson, P. Jonsson, O. Steinvall, "Time-of-flight range profiling using time-correlated single photon counting," Proc. SPIE 6738 (2007)

[55] M. Rungenhagen, M. Kunz, E. Romasew, H.D. Tholl, „Monostatic LADAR demonstrator with micro-optical bidirectional beam control," Proc. SPIE 7483 (2009)

[56] F. Bodrucki, S. Williams, R. Cooke, G. Boreman, "Polarization analysis of retro-reflection from commercial of the shelf (COTS) sensors," Proc. SPIE 10435 (2017)

[57] C.S. Olivera, G.S. Sanchez, C.R. Perez, "Field trials for determining the visible and infrared transmittance of screening smoke," Proc. SPIE 7483 (2009)

[58] S. Lantagne, F. Prel, L. Moreau, C. Roy, C. Willers, "IRCM spectral signature measurements instrumentation featuring enhanced radiometric accuracy," Proc. SPIE 9650 (2015)
[59] S. Scherbarth, A. Thum-Jäger, "Eye safe laser based DIRCM system," Proc. SPIE 7483 (2009)
[60] C.R. Smith, R. Grasso, J. Pledger, N. Murarka, "Trends in electro-optical electronic warfare," Proc. SPIE 8543 (2012)
[61] T. Delmonte, E.J. O'Driscoll, M.A. Watson, D.P. Hand, "Demonstration of a distributed, directed infrared countermeasure source: the multifunctional laser," Proc. SPIE 7115 (2008)
[62] https://www.youtube.com, search for „2018 Guinness World Records - Dances of 1374 Drones"

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