Detecting modulated lasers in the battlefield and determining their direction

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ABSTRACT

Many different lasers are deployed in the battlefield for range finding, target designation, communications, dazzle, location of targets, munitions guidance, and destruction. Laser warning devices on military systems detect and identify lasers striking them in order to assess their threat level and plan avoidance or retaliation. Types of lasers and their characteristics are discussed: power, frequency, coherence, bandwidth, direction, pulse length and modulation. We describe three approaches for laser warning devices from which specific cases may be tailored: simultaneous estimation of direction and wavelength with a grating, wavefront direction only estimation for low light levels with lenses, absolute simultaneous wavelength only estimation with a Fizeau interferometer. We investigate the feasibility and compare the suitability of these approaches for different applications.

Keywords: pulsed lasers, light direction finding, laser warning devices, laser characteristics, types of lasers, gratings, wavefront measurement, Fizeau interferometer

1. INTRODUCTION

The laser, invented around 1960, generates highly coherent light. A laser, such as a much more powerful verion of a laser pointer, can project a MegaWatt-peak-powered light pulse project over long distances at the speed of light, $3\mu s$ per kilometer. The high frequency of light, up to 10^{15} Hertz, permits high bit rate communication that approaches 10^{15} Hertz, if we assume each cycle can be turned on or off. The high coherence enables focusing to spots the size of the wavelength of light, around $1\mu m$; a feature used for removable optical storage or producing high intensity focused energy. Because high energy pulses can be projected efficiently across space at such fast speed it has become necesary to protect potential military targets with laser warning devices. Laser detection can be followed up by evasion or countermeasure. Laser light tends to produce spots of small size relative to the target size, therefore many coordinated, sensors may be needed to provide protection. The challenge is to economically and effectively detect laser light fast enough and sensitively enough to allow a target to be saved.

Another problem arises because the numerous different platforms and situations make standardization difficult. Different branches of the military have different needs, for example, in the Navy, the problem of protecting large targets (ships) from relatively small laser beams is ameliorated by detecting scattered light caused by ocean haze[1]. Lasers may be airborne, vehicle borne, weapons borne, landbased or mounted on rifles. Targets range from personnel or vehicles on the ground, missiles and drones in the air and satellites in space. Global postioning (GPS) satellites guide missiles and locate troops and vehicles. Satellites permit mobile communications and surveillance. Pulses increase peak power relative to average power for increased damage. Modulation permits secure high-bit rate communication and unique identification for avoiding confusion for target designators. A surveillance satellite's solar cells may be damaged or blinded by a ground laser. In section 2.2 we discuss the characteristics of lasers, some of which are measured by the laser warning device. Types of lawsers are discussed in section 2.1. In section 3 we describe three basic approaches for laser warning devices from which systems may be tailored for specific applications.

2. LASER TYPES AND CHARACTERISTICS

The main types of laser are discussed next.

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2.1. Types of laser

- *Laser diodes.* Diode lasers[2] are suitable for the military because they are robust, small (microns), reliable, efficient (typically 50%), mass producible and inexpensive. Laser diodes are used for targeting on rifles, and other low power applications. Semiconductors of different materials provide different frequencies, GaAs infrared lasers at 870nm are inexpensive while GaInP at eyesafe 550nm are more expensive. Power levels of over 50W per cm bar have been achieved: a bar has many synchronized diodes on one substrate. Light from many bars may be carefully combined to provide high-quality tens of kW of power. However, although these shoe box laser diode systems may be expensive, they provide other benefits because their greater efficiency drains less electrical power than alternative types of lasers. More efficient batteries and laser diodes are important research areas.

- *Diode pumped solid state lasers* Diode pumped solid-state lasers[3] provide significant power at infrared wavelength 1062nm (linewidth 28nm) and are widely used for many military applications. Amongst solid-state laser materials Nd:YAG (Neodymium in a host Yttrium aluminum garnet) is the most common and most versatile material because of its high gain and good thermal and mechanical properties. For pumping the solid-state laser, laser diodes are preferred to flashlamps in military applications because they increase system efficiency, component lifetime, and reduce the thermal load for the solid-state laser material which provides higher beam quality and allows higher pulse repetition rates. The laser diodes have approximately 10,000 hour life compare with 200 hours for flash lamps. Diode pumping, although more expensive, also is more efficient because of the good spectral match between the laser-diode emission and the Nd absorption bands. Laser diode arrays with bars are necessary to provide adquate power in the tens of kW.

- *Fiber lasers.* Fiber lasers[4] are developed from Erbium doped fiber amplifiers (EDFA) that are placed every 30km, under manhole covers, in the optical fiiber network for the internet backbone. A fiber optical amplifer consists of several meters of erbium doped fiber that is pumped with laser diodes or by other means. An amplifier is converted into a laser resonator by placing a Bragg grating or other reflector at each end of the amplifier. Advantages of an EDFA based fiber laser are that the wavelength produced, 1550nm, is eye safe; there is room for multiple pumps and they can generate very high powers—tens of kW by cooling with a water jacket. Because of the long length, leading to a large number of longitudinal modes, mode locking can produce femtosecond to nansecond pulses at repetition rates as high a 100GHz with very high peak powers. This performance is more than competitive with mode-locked diode and solid-state lasers. Femtosecond pulses (10^{-15} s) are too short to inflict damage in weapons but do have the property of vaporizing certain materials without passing through a liquid phase—useful for laser-induced breakdown spectroscopy. Other wavelength fiber lasers are feasible and in development. We expect to find more military fiber lasers competing with frequency doubled Nd:YAG lasers.

- *Chemical–oxygen pumped iodine laser.* An oxygen pumped iodine laser[5] can produce TeraWatts of power, or 500J in 500ps pulses. Moreover, conversion efficiency is 15%, an order of magnitude more efficient than solid-state lasers. Hence the US Airborne laser (ABL) program is developing such a laser in a Boeing 747 to destroy ICBMs several hundred miles away that are entering the upper atmosphere from below. The missile skin is at its most stressed and thereform most vulnerable during launch. A downward looking laser of this type is also being tested to destroy tanks in the battlefield. The power is great enough to burn through metal armor and missile housings. For shooting a missile down at long range, the beam must stay on the same spot of the missile for many seconds. This is a formidable task that requires accurate tracking and adaptive optics to compensate for atmospherics turbulence. A sufficiently fast detector could allow the missile to maneuver (such as rotate) to protect itself. The wavelength is $1.3\mu m$. High power gas lasers such as CO_2 are not used because they operate at $10\mu m$ for which reflection from metal can be very high, approaching 95%.

2.2. Characteristics of lasers

A laser warning system is designed to detect one or more of the following relevant laser characteristics.

- *Frequency and power of light.* Fortunately there are a finite number of frequencies that can be easily generated with a laser because frequency is determined by the energy of the photon resulting when an electron falls across a bandgap from a higher energy level to a lower one in a lasing material. The bandgap across which the electron falls is charateristic of the material. The number of low cost easy to process lasing materials is limited and the number capable of generating high power is limited even further. Consequently, in detecting high power lasers we have only a few frequencies to consider. For low power, because of robustness, small size and efficiency, laser diodes are common. Average power is reduced, without decreasing peak power, by pulsing the laser.

  The application also influences the choice of laser frequency, for example eye safe lasers operate at around 1550nm like those in optical telecom. Target designators where an operator points a beam at a target require visible light, while range finders can use infrared, not seen by eye, and hence less likely to alert the target.

- *Bandwidth or temporal coherence.* A charateristic of laser light, not present in other light, is that it contains light close to a single frequency. The bandwidth of the light, called linewidth for a laser, indicates how close the light is to a single frequency. A narrow linewidth or equivalently a high temporal coherence defines the presence of a laser and may provide insight into the laser and its application. Communication lasers have have narrow linewidth so that many wavelength division multiplexed signal can pass through an optical amplifier. Detecting laser light is more difficult in high ambient light caused by sunshine.[6]

- *Direction of laser and spatial coherence.* Spatial coherence is related to the rate at which a laser beam spreads with diffraction and depends on the size of the emitting surface of the laser. Direction of the beam can be determined more precisely for a beam that is spreading more slowly. Beam direction systems are related to wavefront detectors used in adapative optics. The direction of the source can indicate whether the laser is from an airborne verhicle such as a drone or airplane, from a satellite, or from a ground vehicle. Identifying the direction permits immediate retaliation.

- *Pulse and modulation.* Pulses are commonplace for laser weapons because for the same average laser power, greater damage may be inflicted by the higher peak power. A laser warning detector must respond faster to detect shorter pulses. Unfortunately fast response conflicts with high sensitivity which requires long integration times. The platform and application often dictate which is more critical, nethertheless both types of systems may be required in the same installation. Many laser beams are modulated in the battlefield to avoid confusion with other beams, for example target designators. Also, light beams used for communications are modulated with information.

3. LASER WARNING DEVICES

In order to identify a laser threat and select an appropriate response, we wish to simultaneously estimate a number of parameters for the light impinging on a laser weapon warning system. First, accurately estimating the direction of the source allows opportunity for an immedate response to neutralize the source. Second, estimating power and frequency enables us to assess the goal of the laser source and its damage potential from which we can decide on the threat level and correspondinga evasion or retaliation response. Third, the bandwidth in frequency of the source Δf indicates the level of temporal coherence $t_c = 1/\Delta f$ and can provide data on the modulation and pulse width. Indeed, laser light is distinguished from ambient light by its high temporal and spatial coherence.[6]

We describe three approaches that can be used in different circumstances. The simultaneous estimation of direction and frequency with a grating, section 3.1, which is fast but has limited sensitivity to low light levels. Performance may be improved by separating the tasks of estimating direction and frequency. A single lens can replace the grating to provide direction only, section 3.2, as in wavefront detection in adaptive optics. This is more sensitive to low light level because all the light is used purely for direction estimation. An interferometer[7] provides more accurate measurement of frequency only[8] but measures a single frequency ambiguously only within a spectral range. In section 3.3, we select a Fizeau interferometer, because it can simultaneously estimate multiple frequencies unambiguously without mechanical motion. This allows bandwidth measurement and will operate

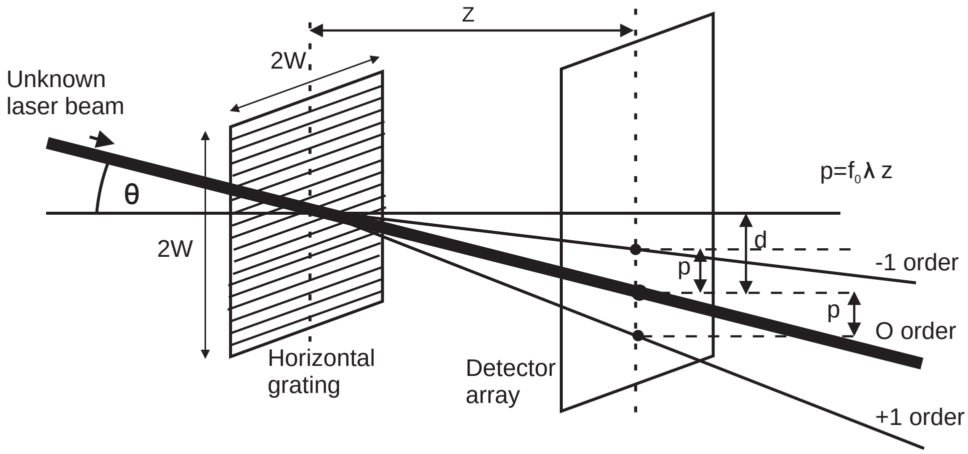

Figure 1. Intensity field from a sinusoidal grating in a laser warning device

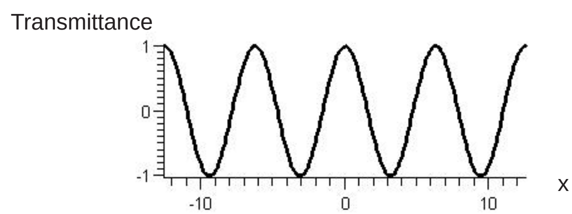

Figure 2. Cosinusoidal grating shape

on very short pulses, assuming fast detectors. However, now, a curved mirror is needed to direct the beam into the interferometer.

We note that laser beams have a cross-section Gaussian intensity distribution which must be included for accurate analysis. Further, beams that carry energy over kilometers through the atmosphere have their diameter expanded to tens of centimeters to reduce the effects of atmospheric turbulence[9,10]. For the most part we do not include Gaussian beams or statistical detection and estimation techniques in this paper for simplicity.

3.1. Grating for simultaneously estimating direction and frequency

A grating is a fast relatively inexpensive means of detecting and simultaneously estimating direction and frequency for a laser beam[11].

Figure 1 shows a ray of the plane wavefront from laser light striking a transmissive cosinusoidal grating of size $2W \times 2W$ at an angle θ in a laser warning device. Light is diffracted by the grating and propagates to a detector array.

The transmission function in the x-direction for the square cosinusoidal grating[12,13] is shown in figure 2.

$$U_{in}(x,y) = \left[\frac{1}{2} + \frac{1}{2}cos(2\pi f_0 x_1)\right] \mathrm{rect}\left(\frac{x_0}{2W}\right) \mathrm{rect}\left(\frac{y_0}{2W}\right) \tag{1}$$

The square bracket represents the sinusoidal grating pattern of spatial frequency f_0 in the x-direction. The rectangular functions represent the finite $2W \times 2W$ square aperture of the grating. The first $\frac{1}{2}$ in equation 1 provides the mean or 0 order diffraction (straight through) in figure 1 which arises because intensity cannot be negative.

Incident light with propagation constant k at an angle θ with the horizontal has a downward propagating component at the grating of $exp\{jksin\theta x_1\} = exp\{j2\pi x_1 sin\theta/\lambda\}$. So the Fourier transform of the intensity immediately after the grating is, from equation (1)

$$
\begin{aligned}
U_{out}(x_0,y_0) &= \mathcal{F}\left[U_{in}(x_1,y_1)exp\left\{\frac{j2\pi x_1 sin\theta}{\lambda}\right\}\right] \\
&= \mathcal{F}\left[\frac{1}{2}+\frac{1}{2}cos2\pi f_0 x_1\right] * \mathcal{F}\left[\mathrm{rect}\left(\frac{x_0}{2W}\right)\mathrm{rect}\left(\frac{x_0}{2W}\right)\right] * \mathcal{F}\left[exp\left\{\frac{j2\pi sin\theta x_1}{\lambda}\right\}\right] \\
&= \left[\frac{1}{2}\delta(f_x f_y)+\frac{1}{4}\delta(f_x+f_0,f_y)+\frac{1}{4}\delta(f_x-f_0,f_y)\right] * (2W)^2\mathrm{sinc}(2Wf_x)\mathrm{sinc}(2Wf_y) * \delta\left(f_x+\frac{sin\theta}{\lambda}\right) \\
&= \left(\frac{2W^2}{2}\right)\mathrm{sinc}(2Wf_y)\left[\mathrm{sinc}\left\{2W\left(f_x+\frac{sin\theta}{\lambda}\right)\right\}+\frac{1}{2}\mathrm{sinc}\left\{2W\left(f_x+\frac{sin\theta}{\lambda}+f_0\right)\right\}\right. \\
&\qquad \left. +\frac{1}{2}\mathrm{sinc}\left\{2W\left(f_x+\frac{sin\theta}{\lambda}-f_0\right)\right\}\right] \qquad (2)
\end{aligned}
$$

If a front-end telescope is used or the beam from the laser is less than the grating aperture size, the Gaussian nature of the laser beam should be included as discussed in section 3.2.

The three orders in the square bracket in the last line of equation (2) correspond to those in figure 1. Assuming sufficient spacing to avoid overlap of diffraction orders we can write the Fraunhofer diffraction far field intensity at the output by introducing scaling for optics, $f_x = x_0/(\lambda z)$ and $f_y = y_0/(\lambda z)$ and by then multiplication by its conjugate,

$$
\begin{aligned}
I_{out}(x_0 y_0) &= \frac{1}{(\lambda z)^2}\left\{\frac{1}{2}(2W)^2\right\}^2 \mathrm{sinc}^2\left(\frac{2Wy_0}{\lambda z}\right)\left[\mathrm{sinc}^2\left(\frac{2W}{\lambda z}((x_0+zsin\theta)\right)\right. \\
&+ \left.\frac{1}{4}\mathrm{sinc}^2\left\{\frac{2W}{\lambda z}(x_0+zsin\theta+f_0)\right\}+\frac{1}{4}\mathrm{sinc}^2\left\{\frac{2W}{\lambda z}(x_0+zsin\theta-f_0)\right\}\right] \qquad (3)
\end{aligned}
$$

The intensity of the far field from a cosinusoidal grating, equation (3), at a far field plane, is illustrated in figure 1.

Information about the wavelength λ of the unknown laser is obtained from the distance p on the detector array in figure 1.

$$\lambda = \frac{p}{f_0 z} \qquad (4)$$

The distance between grating and detector array, z, is known for the system. Information about the unknown laser direction θ is obtained from the distance d in the output detector array

$$tan\theta = \frac{d}{z} \qquad (5)$$

Due to atmospheric turbulence, the image at the detector will wander around and the focus regions fluctuate in size with time. The centroid of the pattern on the image plane is computed. The turbulence effect is in addition to that caused by relative motion of the target and beam source.

3.2. Lens for estimating direction only

A lens can be used in place of a grating to avoid the inefficiences of the sinusoidal grating due to dispersion into three orders. Hence, the lens direction finding system is more sensitive than a grating for finding the direction of low light level laser sources such as arise in munitions guiding lasers or arise with scattering from the atmosphere. This is similar to Hartmann wavefront sensing in adaptive optics[14,15]. Figure 3 shows a Gaussian beam of laser light with spot size W_{lens} striking a lens at an angle θ with the horizontal in a laser warning device.

A Gaussian beam is fully defined by its spot size $W(z)$ (radius of $1/e$ amplitude spot) and the radius of curvature of the phase front $R(z)$.

$$E(x,y,z) = E_0\frac{W_0}{W(z)}exp\left\{-i[kz-\eta(z)]-r^2\left[\frac{1}{W(z)^2}+\frac{ik}{2R(z)}\right]\right\} \qquad (6)$$

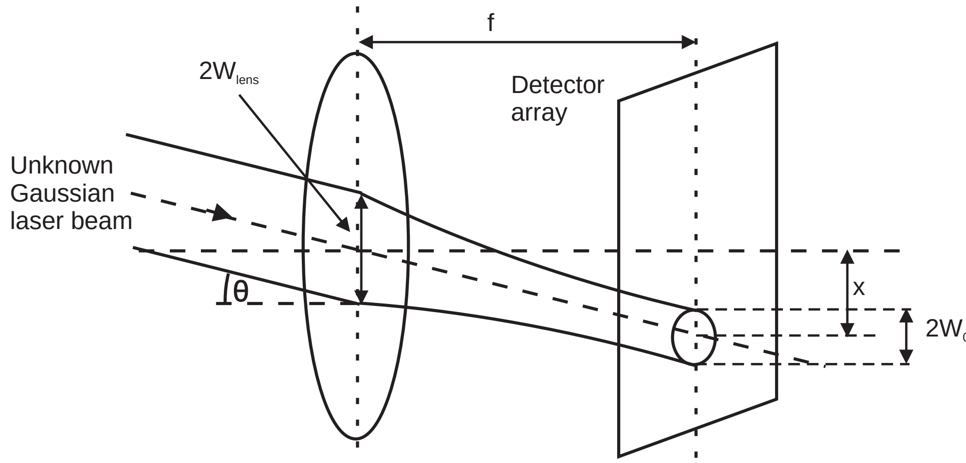

Figure 3. A lens based direction finding system in a laser warning device

where k is the propagation phase constant, W_0 is the bean spot size at the waist (narrowest point), η is the beam divergence angle, and r is the radial direction in the transverse plane. In figure 3 a lens is used to focus a Gaussan beam of spot size W_{lens} to its narrowest spot size (waist) W_0 at the detector[16,17], figure 3.

On passing a Gaussian beam through a lens of focal length f, the spot size W_{lens} remains the same but the radius of curvature R_{in} is reduced by $1/f$. Thus the radius of curvature R of the Gaussian beam exiting the convex lens is given from,

$$\frac{1}{R} = \frac{1}{R_{in}} - \frac{1}{f} \tag{7}$$

Assuming the incoming beam approximates a plane wave because of its great distance from the source, $R_{in} = \infty$, then from equation (7) the radius of curvature of the Gaussan beam leaving the lens is $R = -f$: the negative sign represents a converging beam. The Gaussian beam parameters for the beam exiting the lens are $W = W_{lens}$ and $R = -f$. The Gaussian beam parameters at the detector array are radius of curvature $R = \infty$ and the waist size W_0 which can be written[17] in terms of the input spot size out of the lens W_{lens}, the focal length of the lens f, and wavelength λ,

$$2W_0 = \frac{4}{\pi}\lambda\frac{f}{2W_{lens}} \tag{8}$$

In the same manner as for the grating, section 3.1, the image on the detector array moves around and the spot size varies because of atmospheric turbulence. Consequently the centroid of the spot must be computed to determine the direction of the laser source.

3.3. Fizeau interferometer

A Fizeau interferometer[8] has two off-parallel planar reflecting surfaces separated by a small angle ϕ, figure 4. At any point along z the plates approximate a parallel plate because ϕ is small. So we first consider the parallel plate interferometer in figure 5 in which an unknown laser beam in air impinges at an angle α and is reflected from the top and bottom surfaces. We can determine the increased path length Δs of the bottom surface reflection relative to the top surface reflection in two parts: the part in the glass d_g and the part d_p required to bring the phases together for the output beam.

$$\Delta s = d_g - d_p = \frac{2nd}{cos\beta} - 2d\,tan\beta\,sin\alpha = \frac{2nd}{cos\beta} - 2d\,tan\beta\,n\,sin\beta = 2nd\,cos\beta \tag{9}$$

where we used Snell's law $sin\alpha = nsin\beta$. When the difference in path lengths $\Delta s = m\lambda$ (m an integer), light from the two paths is in-phase and combines constructively for a maximum intensity, while when the difference

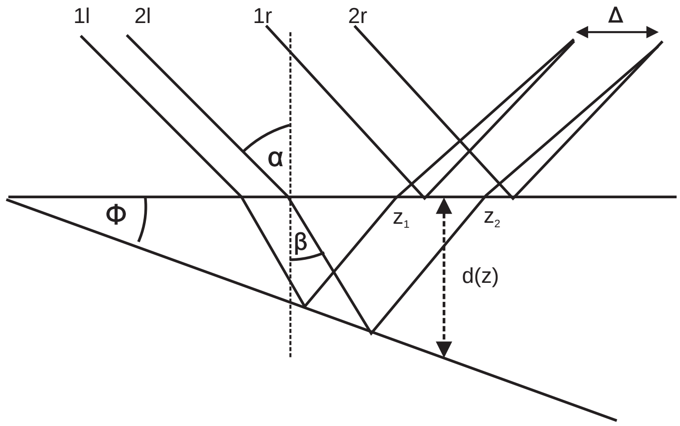

Figure 4. Fizeau interferometer

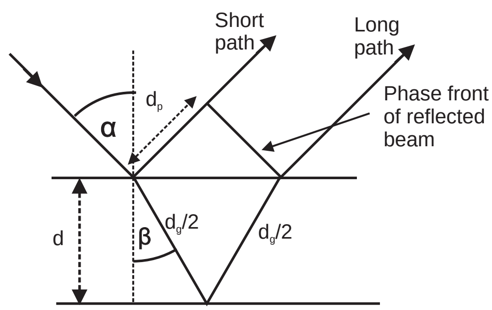

Figure 5. Parallel plate interferometer

in path lengths is $\Delta s = \lambda/2 + m\lambda$, light from the two paths is out-of-phase and combines destructively for a minimum intensity. Setting $\Delta s = m\lambda$ in equation (9) gives

$$m\lambda = 2ndcos\beta \tag{10}$$

In the Fizeau interferometer, the spacing between the surfaces $d(z)$ changes with distance z along the wedge formed and this changes the resonant wavelength λ with distance. By detecting wavelengths of interest in parallel, the Fizeau is more suitable for rapid detection of pulsed laser sources than a resonator that detects only a single frequency. From equation (10) we can write for adjacent peaks,

$$\begin{aligned} 2n[d(z_2) - d(z_1)]cos\beta &= \lambda \\ \text{or} \quad d(z_2) - d(z_1) &= \frac{\lambda}{2n\, cos\beta} \end{aligned} \tag{11}$$

The distance Δ along z between two fringe maxima may be written from figure 4 and equation (11)

$$\Delta = z_2 - z_1 = \frac{d(z_2) - d(z_1)}{tan\phi} = \frac{\lambda}{2n\, cos\beta\, tan\phi} \tag{12}$$

Equation (12) shows that Δ varies with wavelength λ. Further as ϕ is small, the resonant wavelength continues to behave locally at location z like a parallel plate for which λ depends on plate separation $d(z)$. Consequently changing λ will both move the fringes and change the separation of their maxima.

For parallel plate resonators λ can be determined within only one spectral range because of higher order integers m in equation (10). The free spectral range, using conversion from $\delta\nu = c/\Delta$ to $\delta\lambda$ and equation (9) is

$$\delta\lambda = \frac{\lambda^2}{\Delta s} = \frac{\lambda^2}{2nd\,cos\beta} \tag{13}$$

Comparing with a parallel plate interferometer, not only is the Fizeau interferometer better for handling pulsed lasers because it measures many wavelengths simultaneously, but by measuring both the fringe location in z and the separation of the maxima, Δ, we can estimate absolute wavelength and avoid the ambiguity inherent in the periodicity of the parallel plate interferometers.[3]

4. CONCLUSION

All military vehicles, satellites and personnel must have laser warning devices to protect against the increasing laser threat in the battlefield. Many already have such devices. We discuss characteristics of lasers that are measured, detected and estimated by laser warning devices and the plethora of types of lasers and situations. Because of the variety of situations we describe three technical approaches that may be tailored for specific applications: gratings for simultaneously detecting and estimating direction and wavelength of source, lens wavefront detection for only estimating direction, and Fizeau interferometer for only estimating absolute wavelengths. A critical technology that requires future development effort is fast, sensitive photo-detectors over the range of wavelengths used in military lasers.

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