Low-cost detection of lasers

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Abstract. A low-cost method of detecting lasers based on detecting coherence properties of received light is presented. The method uses an unbalanced Mach–Zehnder interferometer with a modulating piezo-mounted mirror in one arm to discriminate against incoherent background light and identify the presence of laser radiation at the nW level against much brighter backgrounds. The wavelength of the coherent input can be determined by comparing the intensities of the modulation frequency harmonics. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.56.11.114104]

1 Introduction

The detection and identification of laser radiation has been pursued for decades, predominantly driven by military requirements. In military scenarios, lasers are used for targeting, range finding, designation, and missile control.[1] The need for lasers with long-range effective operation over many kilometers has meant that high power-pulsed lasers have been used for these purposes. Generations of laser warner receivers (LWRs) have been developed to detect the threat posed by these lasers[2,3] and allow irradiated platforms to initiate appropriate countermeasures determined by the perceived threat. Most LWRs are effective at detecting high energy laser pulses, but they are less effective at detecting low power lasers such as those used with laser beam riders or continuous wave lasers. The last decade has seen the rise of a requirement to detect continuous wave (CW) lasers in both military and nonmilitary scenarios. High power laser diode "pointers" are readily available with powers well in excess of 1 W. The Civil Aviation Authority reports that the number of incidents of aircraft and pilots being illuminated by lasers is increasing every year, with over 1400 incidents in the United Kingdom in 2014.[4] This poses a significant risk to pilot and passenger eyesight with serious potential consequences. Military grade LWRs have limited capability against these particular threats, especially in conditions with bright sunlight background illumination. What is needed is the ability to discriminate laser radiation from background radiation when the laser radiation is potentially orders of magnitude weaker than the background. It is also advantageous to identify the wavelength of the irradiating laser and the direction of the laser source.

Lasers are characterized by three properties:

1. High spectral brightness: a high intensity of radiation in a very narrow spectral window.
2. Well-defined beams: low divergence beams that deliver high intensity over large distances.
3. High coherence: well-defined phase properties.

It is properties 1 and 2 that are generally used to detect lasers. Both these properties can be detected with the use of arrays of detectors, such as a spectrometer for property 1 or a camera for property 2. This is appropriate in the visible band where silicon detection technologies are produced at low-cost, but beyond the silicon detection band (in either direction), detector arrays are considerably more expensive.

Various methods have been suggested to make use of the coherence properties of laser light, allowing it to be discriminated from the incoherent background light. Coherence allows interferometric techniques to be used, allowing a modulation to be detected as the interferometer is adjusted. Crane[5] suggested using an angle-tuned stepped Fabry–Perot etalon as a method for detecting laser pulses. Tilting the etalon system modulates the transmission spectrum for coherent radiation, allowing discrimination to be performed. Fabry–Perot etalon was the early preference [6,7] with Manasson et al.[8] using a Fabry–Perot in the form of an electrooptic crystal whose output could be electrically modulated for coherent illumination at high speed. The Michelson interferometer is another system that has been used to exploit the coherence properties of laser radiation[9,10] where a piezo-mounted retroreflecting mirror was used to observe the modulation envelope and hence determine the source coherence length.

A Mach–Zehnder-type interferometer with an electrooptic phase modulator in one arm was proposed to detect coherent radiation in Ref. 11. This implementation was proposed for use in an optical fiber system. Cohen[12] used a birefringent modulator system to detect weak coherent light against a bright incoherent background. This system involved no mechanically moving parts and had the potential to provide an estimate of the coherent wavelength by examining harmonics of the modulating frequency.

More recently, the coherent properties of laser radiation, when interacting with cosine diffraction gratings, have been used to determine source wavelength and angle of arrival[13–15] by observing diffraction angles. Imaging systems utilising coherence[16] and wide angle detection systems[17] have also been investigated.

The motivation behind this work was to build a low-cost device capable of detecting the coherence properties of laser

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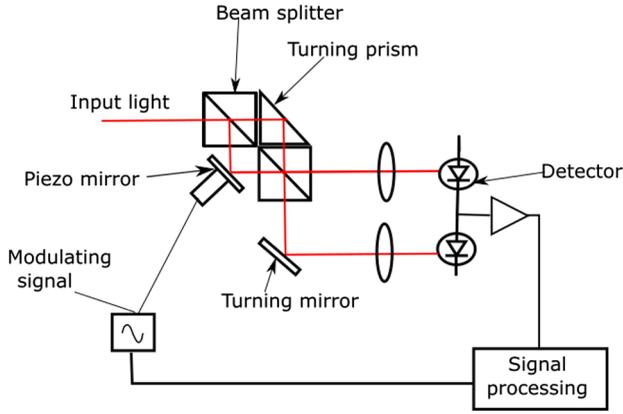
Fig. 1 Schematic diagram of the interferometer.

light. The low-cost element is very important due to the now pervasive nature of the CW lasers. Many of the concepts given in the literature require expensive modulating components or require arrays of detectors. While this is straightforward in the visible part of the spectrum using silicon-based technology, detector arrays in the near-IR are prohibitively expensive. This work overcomes these cost issues using individual detectors rather than arrays and using an inexpensive modulation mechanism. Thus, the cost of an entire detection might be below $1000, which is less than the cost of an array or modulator given the current state of technology.

2 Coherence Modulation

The concept used in this work is to produce an interferometer with a path length difference between its two arms that exceeds the coherence length of the background light entering the interferometer. This will typically be a Mach–Zehnder-type interferometer. Into one arm of the interferometer is placed a phase modulating element such as an electro-optic phase modulator or a piezo-mounted mirror. A regular modulation signal applied to this element produces a related modulation at the output of the interferometer only if light with a coherence length longer than the path difference between the arms is present. Thus, detection of a modulating signal component is an indication that laser illumination (or, more specifically, long coherence length illumination) is entering the interferometer. A schematic representation is shown in Fig. 1. This system modulates the length of one arm using a piezo-mounted mirror. The modulating signal exists at both output ports of the final beam splitter, but these signals are out of phase with each other; hence, a balanced detector system can give an additional factor of 2 to the detection sensitivity. Various possibilities exist for making use of the two output ports, such as using detectors with different spectral responses to produce a system with much wider sensitivity.

3 Theory

Consider a Mach–Zehnder interferometer with arm lengths L_1 and L_2, which need not be equal, and a piezo driven mirror in arm 2 such that L_2 varies with time (t). The amplitude of an electromagnetic wave of frequency ω, wavelength λ, and amplitude E, split between the 2 arms is

$$A_1 = E\{[1 - R(\lambda)]\}\cos\left(\omega t + \frac{2\pi}{\lambda}L_1\right), \tag{1}$$

$$A_2 = ER(\lambda)\cos\left[\omega t + \frac{2\pi}{\lambda}L_2(t)\right], \tag{2}$$

where $R(\lambda)$ is a wavelength-dependent reflectivity for the beamsplitters. When recombined at a detector D following the second beamsplitter, the amplitude at the detector is

$$A_d = R(\lambda)A_1 + [1 - R(\lambda)]A_2. \tag{3}$$

The detector measures the time averaged intensity

$$I_d = \frac{1}{T}\int_0^T \langle A_d^2\rangle, \tag{4}$$

which results in a temporally varying intensity

$$I_d = \frac{\{E[1 - R(\lambda)]R(\lambda)\gamma\}^2}{T}(1 + \cos\{k[\Delta L(t)]\}), \tag{5}$$

where γ is a factor representing reflection loss, $k = 2\pi/\lambda$, and ΔL is the difference $L_1 - L_2(t)$.

This is the familiar cosinusoidal modulation of an interferometer transmission, and the temporally modulating signal relating to the path length difference is the indicator that coherent light is passing through the interferometer.

The piezomirror is subject to a sinusoidal modulation voltage of amplitude v_m and frequency f_m. The response of the piezo is p μm V^{-1}, and the path length change that is generated is increased by a factor $\sqrt{2}$ due to the mirror being at a 45 deg angle. Thus, the path length difference is

$$\Delta L(t) = L_1 - L_2(0) - v_m p\sqrt{2}\,\sin(2\pi f_m t) - v_{\text{off}}p\sqrt{2}, \tag{6}$$

where v_{off} is a dc offset voltage applied to the mirror.

Combining constant terms into a factor C, the detector intensity is written

$$I_d = \frac{\{E[1 - R(\lambda)]R(\lambda)\gamma\}^2}{T}(1 + \cos\{k[v_m p\sqrt{2}\sin(2\pi f_m t)] + C\}). \tag{7}$$

By choosing the offset voltage such that the effectively $C = \pi/2$, we arrive at the form

$$I_d = \frac{\{E[1 - R(\lambda)]R(\lambda)\gamma\}^2}{T}\{1 + \sin[kv_m p\sqrt{2}\sin(2\pi f_m t)]\}. \tag{8}$$

Using the Bessel function identity

$$\sin(z\,\sin\,\theta) = 2\sum_{k=1}^n (-1)^k J_{2k+1}(z)\sin[(2k+1)\theta], \tag{9}$$

where the functions J_k are Bessel functions of the first kind, the intensity at the detector can be represented in terms of harmonics of the modulation frequency.

$$I_d = I_o[1 - 2J_1(kv_m p\sqrt{2})\sin(2\pi f_m t)$$
$$- 2J_3(kv_m p\sqrt{2})\sin(2\pi 3 f_m t) + \ldots]. \tag{10}$$

The initial multiplying terms have been incorporated into the single term I_0.

The size of the harmonic terms is determined by the Bessel functions which are dependent on the amplitude of the modulating voltage (v_m) and the wavelength. Therefore, for a known value of v_m, the wavelength can be obtained by measuring the harmonic amplitudes. Because Bessel functions will have multiple solutions, the wavelength is best estimated by considering a ratio of the harmonic amplitudes. A similar approach was considered by Cohen[12] using a polarization modulator but with incorrectly labeled harmonics, thus confusing what was actually being measured. The power spectrum of the sampled output waveform produces terms proportional to the square of the Bessel function amplitudes, and thus the ratio of the third harmonic to the modulation frequency is given by

$$H_{13} = \frac{J_3(kv_m p\sqrt{2})^2}{J_1(kv_m p\sqrt{2})^2}. \tag{11}$$

Low coherence interferometry and optical coherence tomography are techniques that utilize optical sources with a limited coherence length,[18,19] such as LEDs where the spectral bandwidth might be of the order 10 nm. By controlling the length of a reference arm within an interferometer, interference effects can only be observed when the arm lengths match to within the coherence length of the source. Equally, no interference effects can be observed from broadband sources if the difference in arm length is deliberately made longer than the coherence length. In this way, a detector for laser radiation, where coherence lengths can be long, can discriminate against bright broadband sources that cannot contribute to the modulation signal.

The coherence length of a source with central wavelength λ and spectral width $\Delta\lambda$ is given approximately by

$$l_c = \frac{\lambda^2}{2\Delta\lambda}. \tag{12}$$

For visible light with a wavelength of 600 nm and a spectral width of 400 nm, the coherence length is of the order 0.5 μm. A difference between the interferometer arm lengths greater than this is all that is required to prevent significant modulations occurring from the background illumination.

4 Implementation

A compact version of the interferometer was constructed and is shown schematically in Fig. 1. It is composed of a pair of 1-cm cube beam splitters connected via a turning prism in one arm and a piezo-mounted mirror in the other. This readily provides an optical path length difference of a few mm between the two interferometer arms, well in excess of that needed to ensure no background contributions. The piezo-mounted mirror was 7 mm in diameter and forms the limiting aperture for the system field of view. The output from each arm is sent to one of a pair of balanced detectors (Thorlabs) with a 30-dB level of cancellation. This difference signal is sent to a data acquisition unit, where it is digitized and sent to a computer for signal processing. Two versions of this system were constructed, one for visible wavelengths and a second for near-IR wavelengths. The near-IR version replaced the optics with near-IR versions, and the detector was a balanced pair of InGaAs detectors. The modulation signal was provided directly to the piezo mirror by a function generator.

5 Signal Processing

Two approaches were used to detect modulating signals: lock-in detection and Fourier transform analysis. Lock-in detection is known to be good for extracting weak regular signals where large amounts of noise are present and is therefore well suited to finding weak modulating coherence signals against bright incoherent backgrounds. Lock-in detection was implemented entirely digitally within software written using LabView. The detected signal is multiplied by the modulation signal, low pass filtered, and then integrated for a sufficient length of time. The modulation signal was captured along with the detector signals and a scaled version was used to provide signal gain. Higher harmonic versions of the modulation frequency could be generated and used in parallel to determine the level of harmonics present in the detector signal. The noise from the output is related to the width of the low pass filter used and the intrinsic noise from the detector. The system was tested by detecting weak scattered laser light against a bright spectrally broad background provided by a Halogen lamp.

The second processing technique involved identifies spectral features in the modulation frequency domain by simply taking the Fourier transform of the captured detector time series. A rolling average spectrum was generated by summing consecutive frequency spectra. Coherent signals were identified by examining the spectral amplitudes at the modulation frequency and its harmonics. The ratio of the third and first harmonics could then be easily extracted.

To measure the system sensitivity, light from a fiber-coupled laser diode at 635 nm was directed into the interferometer and attenuated with neutral density filters. Signal and noise levels were observed using integration times that were practically realistic—around 1 s for both processing methods. The sensitivity results are plotted in Fig. 2 for the visible sensitive system. This is an interesting plot showing that the ultimate sensitivity for the system (S:N=1) is around 1 nW and that the lock-in (PSD) processing is slightly more
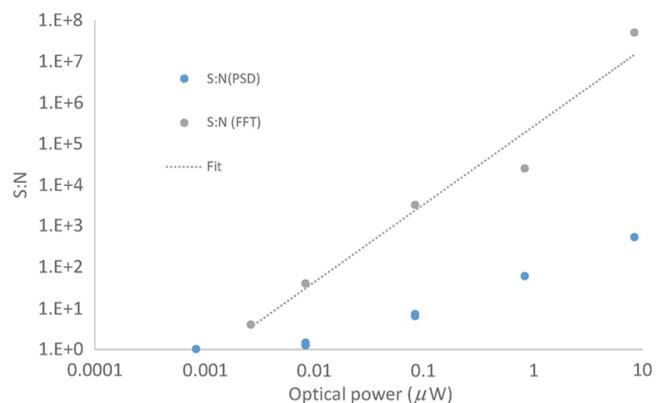
Fig. 2 Signal-to-noise measurements defining the sensitivity at 635 nm using different signal processing approaches.
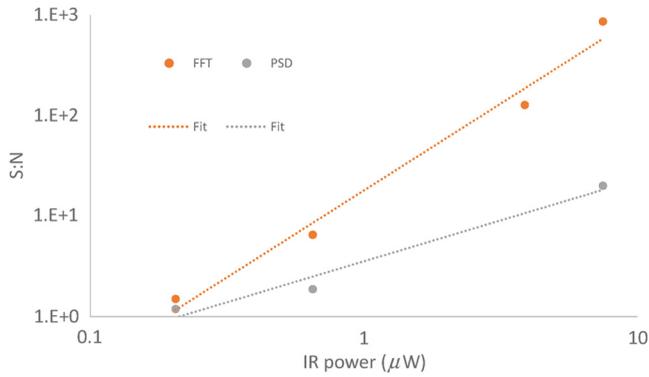
Fig. 3 Sensitivity measurements for the near IR version using 1.5 μm light.

sensitive than the FFT approach. However, above the noise limits, the FFT gives larger signal-to-noise values coupled with the fact that this technique is much simpler to implement and requires less processing; this is therefore the most attractive approach (dependent on application). The sensitivity is dependent on the physical size of the entrance aperture, which is limited by the size of the beam splitter cubes and the piezo mirror. In the present case, there are no objective lenses adding optical gain—this is not necessary when lasers are directed into the system—but future systems could use this to improve sensitivity. The sensitivity is also dependent on the responsivity of the detector, which increases at longer wavelengths.

The sensitivity data for the near-IR version is shown in Fig. 3. This clearly demonstrates a higher optical power requirement with a sensitivity limit around 300 nW. This arises mostly because the IR version of the balanced detector has a higher noise equivalent power level (16 pW Hz$^{-1/2}$ for InGaAs versus 3.6 pW Hz$^{-1/2}$ for Si). However, it was noted that, for the visible system when detecting modest laser power of the order μW s, the laser intensity itself was the main contributor to the noise. The application requirements for sensitivity will therefore drive the physical design of the IR laser detector, i.e., through choice of aperture size.

Modulation frequency signals seen against a bright spectrally broad background for a variety of laser powers can be seen in Fig. 4. Light from a Halogen lamp was directed via a fiber bundle into a beam splitter where it was combined with the beam from a diode laser (635 nm) and directed into the interferometer. Figure 4 shows the modulation frequency spectra observed along with an image of the light exiting the second port of the combining beamsplitter. This shows the relative brightness of the laser and the background. A series of harmonics of the halogen lamp modulation frequency (100 Hz) can be seen where the laser power is low. The modulation frequency was chosen to be 637 Hz to allow discrimination from the sixth harmonic of the lamp signal. The presence of the laser can still be clearly detected even though the background intensity is significantly brighter, thus showing how coherence detection provides advantages over intensity-based detection methods.
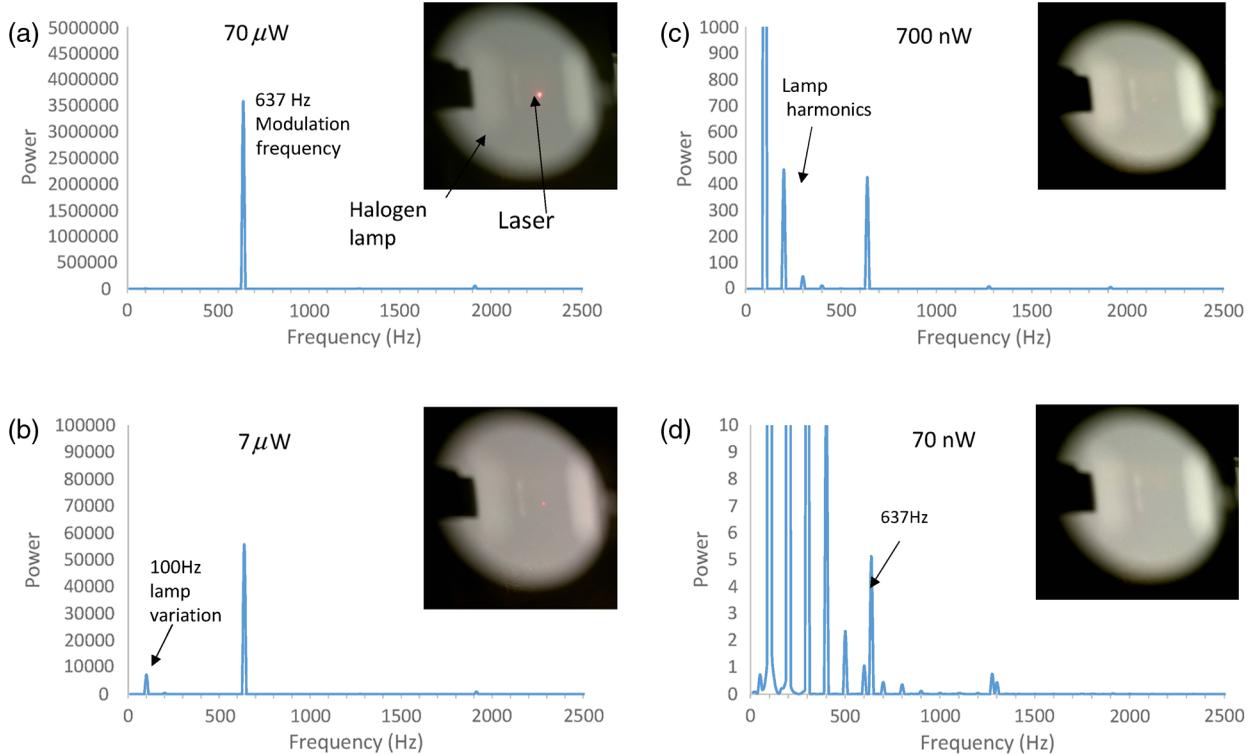

Fig. 4 Modulation signals against a bright background for differing laser powers. In each plot, the inset picture is a photograph of the background and laser, after coupling through a beam splitter. (a) Laser power 70 μW, strong modulation signal, easily observed against bright background. (b) Laser power 7 μW, similar intensity to background. (c) Laser 700 nW, intensity variations at 100 Hz from the halogen source and higher harmonics observable. (d) Laser power 70 nW, very much weaker than background, known modulation frequency distinguishable from harmonics.
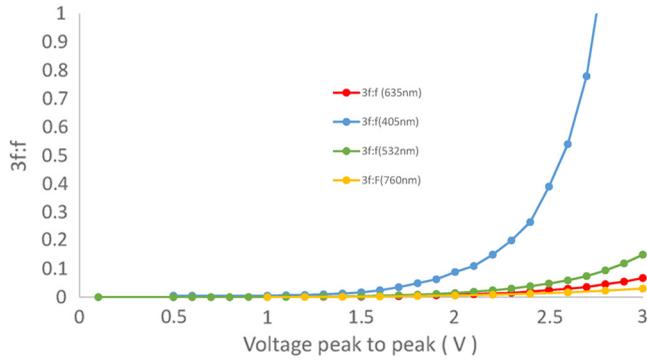
Fig. 5 Measured ratios of third harmonic to fundamental power for a set of wavelengths and modulation amplitudes.

Fig. 6 Signal strength variation with modulation amplitude for laser light at 635, 532, and 405 nm.

6 Determination of Laser Wavelength

According to the theory set out earlier, the amount of modulation frequency that the third harmonic present depends on the wavelength being detected and the amplitude of the modulation. For a given modulation amplitude, the ratio of the third harmonic power to the power in the fundamental frequency is an indicator of the laser wavelength. This was examined for a set of wavelengths at 405, 532, 635, and 760 nm, where the ratio was measured for a range of modulation amplitudes. The results can be seen plotted in Fig. 5. From this plot, it is clear that, for all values of modulation amplitude, the ratio of third harmonic to fundamental increases as the wavelength decreases. In taking these measurements, care was taken to minimize the second harmonic power by adjusting a DC offset voltage applied to the piezo, for when the second harmonic is strong it can distort the ratio of the third to first harmonics. These measurements clearly show that information about the wavelength can be obtained with no extra optical complexity. However, in practice, the ratio was not stable and was prone to drift as the interferometer drifted. It did, however, give an indication of the approximate wavelength.

The harmonic ratio curves shown in Fig. 5 were compared with the model outlined earlier. The harmonic ratio for known wavelength and amplitude was calculated with variable parameters being the piezo response and a scaling factor. Good fits to the ratio curves could be obtained for all wavelengths with consistent values for the piezo response ($p = 0.05 \ \mu\mathrm{m\,V}^{-1}$), but a different scaling factor was required for each wavelength. The source of this wavelength-dependent scaling factor is not yet confirmed but is thought likely to be due to the nonlinear piezo response.

7 Optimizing with Wavelength

The amplitude of the modulation frequency component is given by the first-order Bessel function term

$$J_1\left(\frac{2\pi}{\lambda} v_m p \sqrt{2}\right) \qquad (13)$$

and is therefore wavelength-dependent.

The use of the harmonic ratio to determine wavelength suggests using a modulation voltage amplitude set for the longest wavelength to be detected, producing larger values of harmonic ratio for smaller wavelengths and redistributing the power into the higher harmonics. There is also
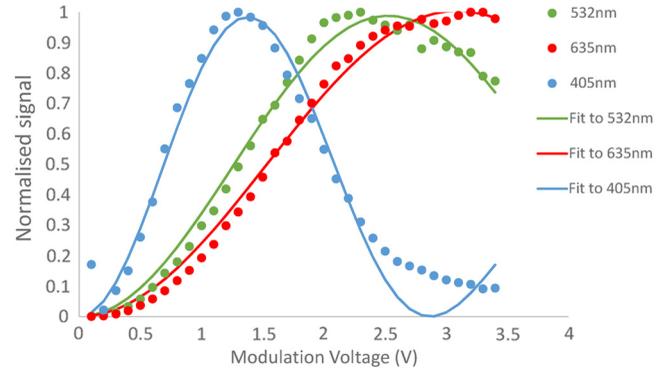
a requirement for the modulation amplitude to be less than the value at which the Bessel function goes to zero, which would occur at the smaller wavelengths and lead to large and ambiguous ratios. This, however, is not optimum from a detection sensitivity point of view. The best sensitivity occurs when the Bessel function is maximized for the first harmonic; thus, there is an optimum modulation amplitude. This occurs when the movement of the mirror induces a path length difference of half the incident wavelength between its maximum and minimum modulation positions. The only way to ensure maximizing this for an unknown source is to scan the modulation amplitude and observe the variation in modulation amplitude. This would also serve as another estimator of the input laser wavelength. There is also a requirement that the second harmonic term is minimized to ensure consistency. This variation of signal amplitude has been observed and can be seen in Fig. 6, where the modulation amplitude was ramped and the signal response at the fundamental modulation frequency was recorded. The solid lines in this plot are a best fit to the square of a first-order Bessel function as shown in Eq. (13). It can be seen that sensitivity at the fundamental frequency will be very small for 405 nm when the sensitivity is high for 635 nm. Obviously, higher order harmonics are present for 405 nm, but these are never as strong as the fundamental; therefore, sensitivity is reduced. It can be seen that, at a modulation amplitude of 2.3 V, the response of the system is no longer linear. This arises from the direct driving of the piezo, which responds in a capacitive manner. Nevertheless, this adequately displays the effect that wavelength sensitivity is dependent on modulation amplitude.

8 Conclusions

The motivation behind this work is to demonstrate that the low-cost detection of lasers can be implemented using coherence detection rather than intensity detection. This is particularly relevant to the detection of near-IR lasers beyond the detection capability of silicon, where arrays of detectors are still relatively expensive. A simple Mach–Zehnder interferometer with different optical path lengths in each arm is able to nullify the high intensity of background light due to its incoherence. A regular modulation of the length of one arm using a piezo-mounted mirror can produce a modulating intensity output, which arises from the presence of coherent light with a coherence length greater than the path difference between the arms. This is easily distinguishable against

natural background sources. However, artificial sources often have a residual intensity modulation and exhibit frequencies at multiples of the mains supply frequency. This intensity modulation appears at the output of the system; therefore, the choice of modulation frequency should be chosen to avoid confusion with higher harmonics of the source. In practice, this modulation frequency will be limited by the response of the piezo, particularly if thick mirrors are used and limit the modulation frequency to around 1 kHz. Light traveling through a free space can be subject to scintillation even at these frequencies and would therefore affect the sensitivity of such a system. Therefore, engineering a system with a modulation frequency of around 2 kHz would be a sensible precaution against possible scintillation issues.

Detection sensitivity levels of around 1 nW have been measured for visible wavelengths, and tens of nW have been detected against bright backgrounds. This sensitivity level will increase with more sophisticated optical designs, such as using a larger input aperture to capture scattered light and avoiding the limiting aperture currently provided by a small piezo mirror. Not only has sensitive detection been demonstrated but wavelength determination is also possible and requires no additional system components. In the case of pilots, this wavelength determination could be used to fine tune wavelength-specific protective measures rather than a crude red, green, or blue assessment, leading to a potentially incorrect inference of the wavelength. The ability to detect weak laser light against a bright background would be helpful in detecting laser light scattered from surfaces, which will be much weaker than direct illumination. This will allow advance warning that a laser may be sensing or targeting in the local vicinity, enabling protective measures or countermeasures to be implemented.

Thus, this simple low-cost approach to coherence detection offers a capability to detect weak CW lasers not offered by intensity-based LWRs and can also offer additional functionality in the form of wavelength determination. In the current times, when high power laser diodes are readily and cheaply available, this could prove to be a useful technique.

Acknowledgments

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