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An electronic differential light wavelength sensor based on Michelson interferometer

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There are several cases in which the measurement of light frequency changes is necessary. For example, it is noteworthy to define the stability of output frequency (wavelength) of a laser beam. Besides, high speed light frequency sensors can be used in optical frequency modulation which has advantages including low cost, high data rate and low noise modulation. Nowadays, for transmitting optical signals, the usual method is converting the message signal to a digital signal and transmitting it with a special digital modulation and after receiving, it will be converted to an analog signal. The mentioned sections are complex and expensive. Sending a digital signal (pulse) through a nonlinear optical medium (optical fiber) may cause undesirable effects such as generating harmonics and energy dispersion in the medium. In this case, we are able to send an analog message as an analog optical signal by a tunable laser diode and receive it by this sensor. Also transmitting digital signals with usual digital modulations such as frequency shift keying will be possible. In this work, we present a new differential light frequency sensor based on an integrated Michelson interferometer whose precision in detecting wavelength changes is less than 0.001 nm.

Keywords: wavelength, Michelson interferometer, sensor.

1. Introduction

The visible light wavelengths are between 0.4 to 0.7 μm. Hence, the light frequency is between 405 to 790 THz. In this case, there is no real time instrument with the ability to measure the optical frequency of light. Nowadays there are several optical modulation methods for transmitting data from one point to another point. Most of these methods are based on switching and change in light phase. Mach–Zehnder interferometer (MZI) is an important part of common optical modulators which can change the amplitude of output light wave proportional to the applied voltage. As shown in Fig. 1, this device consists of two balanced arms which play a role as optical waveguides and a light beam splitter. The device changes the amplitude of the output light wave by creating a delay in one arm. Input light falls on the beam splitter and splits in

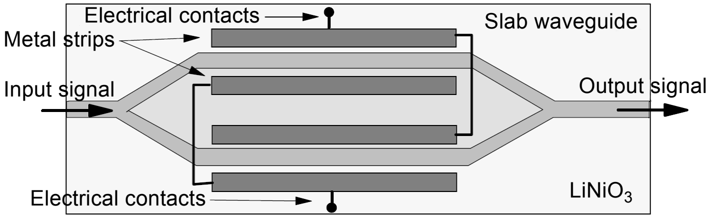

Fig. 1. Configuration of a typical MZI [1].

two similar beams and these two split beams travel in two arms independently. In one arm (the upper one) we have an electro-optic medium. Here, the main properties of the electro-optic medium changes its refractive index by changing the applied voltage. Changing refractive index of this medium causes the change in optical path and hence introduces a delay in the upper arm. The delay will cause a phase shift of the light in the upper arm. The delay depends on the voltage applied to the delay generator (electro -optic media in the upper arm). Hence, after interference and recombination, the amplitude of the output light changes. This is the principle of MZI and the speed of transferring data using this device is limited by the speed of the delay generator element [1]. Current researches aim to transfer information using the amplitude and phase to obtain a higher data rate. Binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) are two modulations in which data is not transferred only by amplitude [2].

In this work we present a new device to implement the optical frequency modulation (FM) which is simpler than available systems (see Fig. 2). For instance, to transmit and receive voice in existing optical communication systems, there is one part to convert analog signals to digital ones and at the receiver side there is another part to convert a digital signal obtained from the Mach–Zehnder demodulator to an analog signal.

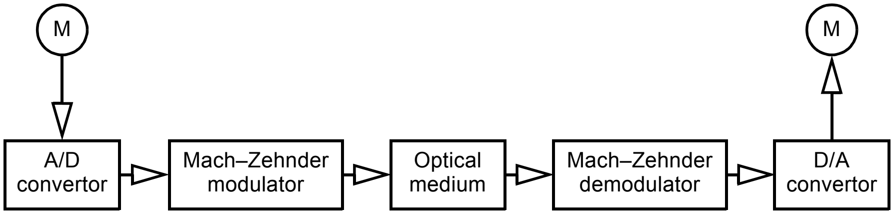

Fig. 2. Typical recently used optical communication block diagram (M – massage).

By implementing FM optical modulation, it is possible to transmit and receive an analog signal simpler than other systems. In the other words, there is no need to have A/D and D/A convertors at transmitter and receiver points. Figure 3 shows the optical FM communication system block diagram.

To implement an optical FM data transfer system, a device is needed which converts data to optical frequency. Hence we need a voltage controlled optical frequency synthesizer to convert a message signal to an optical frequency whose performance is

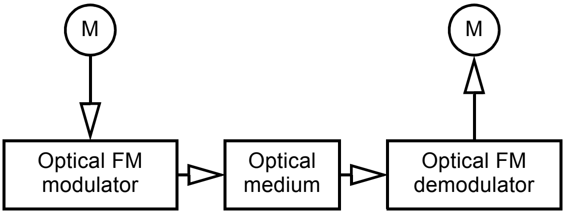

Fig. 3. Block diagram of an optical communication system.

similar to a voltage controlled oscillator (VCO) in radio FM transmitter systems. This is possible in tunable solid state lasers or tunable fiber lasers [3, 4]. At the receiver we need a device to convert optical frequency to voltage so that it can demodulate the message from the optical carrier frequency. A differential light frequency sensor can play a role as an optical frequency to a voltage convertor in the receiver side. By considering differential light frequency sensor applications in communication systems, the device must be of high speed and low cost. In this research, our objective is to design and implement this device.

The mentioned device can be used in experimental applications to detect small changes in wavelength of a laser output beam or investigate laser output beam frequency (wavelength) stability against changing other parameters and conditions [5, 6]. For example, to find wavelength stability of a laser against changing the device temperature and obtaining a wavelength-temperature curve, the presented differential light frequency sensor is an effective tool.

2. Michelson interferometer based wavelength meter

A scheme of a Michelson interferometer is shown in Fig. 4. The incident light is split in two ways each with 50% amplitude of incident light and travels two different paths called L_1 and L_2. After being reflected by mirrors, they are recombined at the beam splitter and generate an interference pattern as light and dark fringes. The luminance of the pattern is a function of wavelength and the geometrical distance between the beam splitter and the mirrors.

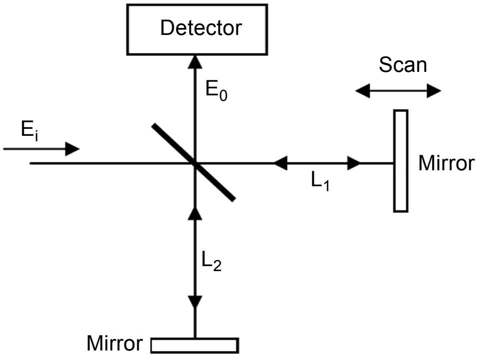

Fig. 4. Michelson interferometer [7].

When two split beams are perpendicular to the mirrors, the difference optical paths are

$$\Delta = 2L_2 - 2L_1 = 2d \tag{1}$$

However, if the beams are incident on the mirrors at the angle θ, the optical path difference is

$$\Delta = 2d\cos(\theta) \tag{2}$$

If the geometrical position of scanning mirror changes, the luminance of the interference pattern under this geometrical change is different and the optical path difference d_1 is replaced by d_2. If we consider $d_1 = 0$, then the difference between d_1 and d_2 is

$$d_2 - d_1 = d_2 = d \tag{3}$$

If we consider d as a geometrical change of the scanning mirror, under this change the luminance of pattern swings m times between light and dark regions. As a result, it is clear that the wavelength can be determined by

$$2d = m\lambda \tag{4}$$

So λ can be determined by measuring the displacement of a moving mirror and counting m fringes.

In a typical wavelength meter based on the Michelson interferometer, a photodiode is used to convert a luminance interference pattern to an electrical signal. At this photodiode, the received optical field will be obtained by

$$\begin{aligned} E_0 &= \sqrt{1-\alpha}\,\sqrt{\alpha}\,E_i[e^{j(2\beta L_1 + \varphi_1)} + e^{j(2\beta L_2 + \varphi_2)}]e^{j\omega t} = \\ &= 2\sqrt{\alpha(1-\alpha)}\,E_i e^{j[\beta(L_1 + L_2) + 0.5(\varphi_1 + \varphi_2)]}\cos[\beta\Delta L + 0.5(\varphi_1 + \varphi_2)]e^{j\omega t} \end{aligned} \tag{5}$$

where E_i is the applied optical field, α is the power splitting rate of the beam splitter, n is the refractive index, $\beta = 2\pi n/\lambda$ is the propagation constant, $\Delta L = L_1 - L_2$ that is length difference between arms, ω is the optical frequency and φ_1 and φ_2 are initial phase shift of arms introduced by a beam splitter and mirrors.

Since the photodiode is a square law detector, the current of photodiode is proportional to the received optical power

$$I = \Re|E_0|^2 = 2\alpha(1-\alpha)P_i\Re[1 + \cos(2\beta\Delta L + \Delta\varphi)] \tag{6}$$

where $\Delta\varphi = \varphi_1 - \varphi_2$ is the initial phase difference between two arms where $\Delta L = 0$ and $\Re$ is the responsivity of photodiode. So it is clear that the photocurrent changes by changing length of each arm.

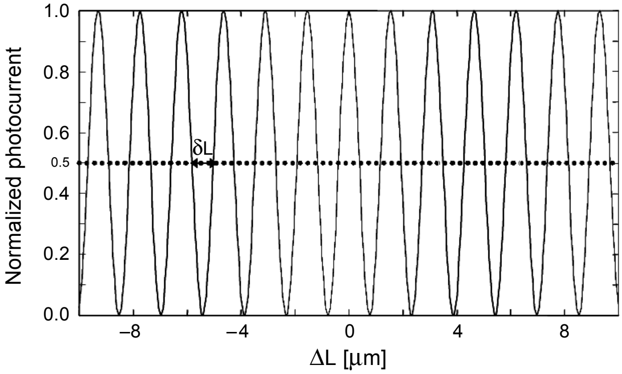

Fig. 5. Curve of normalized photocurrent I as a function of ΔL for 1500 nm optical wavelength [7].

In the simplest case, we have a single optical wavelength λ. By considering Eq. (6), the photocurrent is alternating by moving the scanning mirror. By analyzing the photocurrent I as a function of wavelength, Fig. 5 is obtained. For example, if the distance between two points in which the photocurrent is half-maximum is δL, then $\cos(4\pi \Delta L + \Delta\varphi) = 0$ and hence

$$4\pi \frac{\delta L}{\lambda} = \pi \tag{7}$$

So we can obtain optical wavelength by $\lambda = 4\delta L$.

In fact, for determining optical wavelength, the scanning mirror needs to be moved up to half wavelength. But in typical wavelength meters this change is much longer than this amount to reduce measured noise associated with optical wavelength. Under longer scanning we will record multiple δL and estimated measured δL can be obtained by averaging δL values. So far, we discussed the simplest case of Michelson wavelength meter whose optical signal has a single wavelength. Now assume that the optical signal consists of two wavelengths λ_1 and λ_2 with optical frequencies of ω_1 and ω_2, and amplitude of each signal is equal to $E_0/2$, thus we have:

$$E_0 = 0.5E_i\left[e^{j\beta_1(L_1+L_2)}e^{j\omega_1 t}\cos(\beta_1\Delta L) + e^{j\beta_2(L_1+L_2)}e^{j\omega_2 t}\cos(\beta_2\Delta L)\right] \tag{8}$$

In Equation (8) the initial phase difference is ignored for simplicity and 50% splitting ratio of an optical coupler is assumed. The photocurrent can be determined by

$$I = \Re P_i\left[1 + \frac{\cos(2\beta_1\Delta L) + \cos(2\beta_2\Delta L)}{2}\right] \tag{9}$$

In obtaining Eq. (9), we ignored the time dependent factor $e^{j(\omega_1 - \omega_2)t}$, because the speed of change in interferometer arms is much slower than fast random changing in phase.

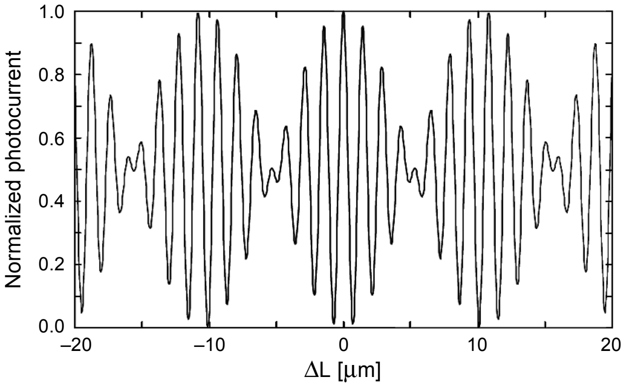

Fig. 6. Photocurrent for an optical signal with 1350 and 1550 nm.

Figure 6 shows the photocurrent for an optical signal with two wavelengths. For determining the wavelengths, we need to measure δL for each wavelength. In this case we need to apply the fast Fourier transform (FFT) on photocurrent to measure δL for each element.

An important factor here is to measure the displacement of the moving mirror accurately. In fact, the accuracy of the measured wavelength directly depends on the accuracy of the measured d. A good solution for measuring the displacement of a moving mirror is to use a stable wavelength laser beam with a known wavelength as a calibrator beam, as shown in Fig. 7. The displacement d will be obtained by Eq. (4) by counting m' corresponding to the interference pattern.

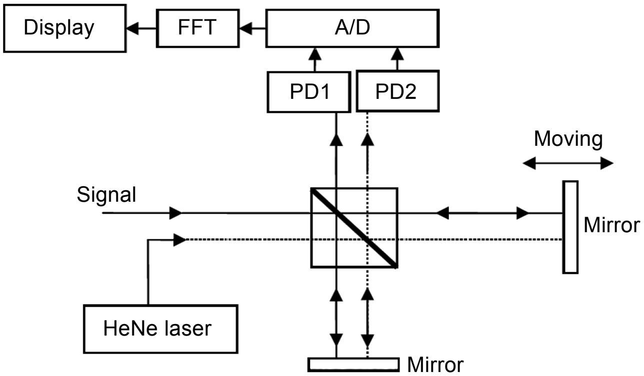

Fig. 7. Optical wavelength meter based on Michelson interferometer with HeNe calibrator laser. Two photodiodes are used to count fringes [7].

The Michelson interferometers are implemented by optical fiber in some optical communication networks and newly on silicon wafers for optical micro-probes. Figure 8 shows the Michelson interferometer that is implemented on a silicon wafer. The effective area of this sensor is 550 μm×200 μm [8].

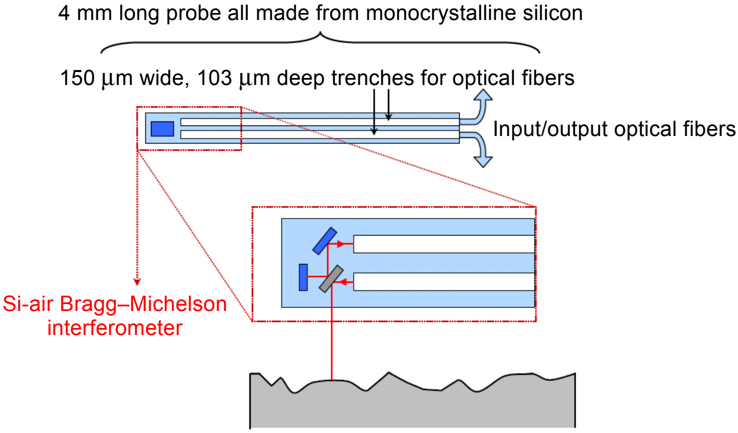

Fig. 8. Schematic illustration of the device and its operation principle as an optical probe for profile measurement based on the Michelson interferometer integrated at the probe end [8].

Now we can implement the Michelson interferometer and a photodiode on a very small piece of silicon to sense changes in light wavelengths. The type of the photodiode depends on a spectral range in which the sensor should work. Regarding the spectral response of photodiodes, for wavelengths of 400 up to 900 nm, Si photodiodes are suitable and for longer wavelength in an infrared region, InGaAs photodiodes are appropriate [9].

3. Device design

Now consider the Michelson interferometer with fixed mirrors. If a monoharmonic light falls on the beam splitter, the luminance of the interference fringes will get a fixed value. If we change the incident light wavelength, the luminance of the interference fringes will change. Figure 9 shows the resultant luminance for two different wavelengths.

In a such system, our analyses show that the luminance of interference fringes is a function of wavelength of incident light and this is the basic principle of this work. The differential light frequency measurement sensor will detect changes in the wavelength by measuring luminance changes on a Michelson interference pattern. Figure 10 illustrates the luminance of interference fringes against changes in the wavelength.

Looking at Fig. 10, we can see that the luminance of 500.0000 up to 500.000440 nm is increasing and then starts decreasing to 500.00065 nm. At first we may conclude that a good working area for the sensor is to make a decreasing area larger in Fig. 10. But as Fig. 10 illustrates, by increasing the wavelength, we have some homonym half sinusoid shapes with a decreasing amplitude. The decreasing amplitude is an undesirable effect which limits this sensor bandwidth. For instance, assume that this sensor is intended to be used in an optical FM modulation. The tunable laser wavelength stability must be more than 0.00003 nm (0.1 of the first cycle). However, such commercial laser is not available today. If we obtain a luminance-wavelength function for a wider range for wavelength change, it will be similar to Fig. 11.

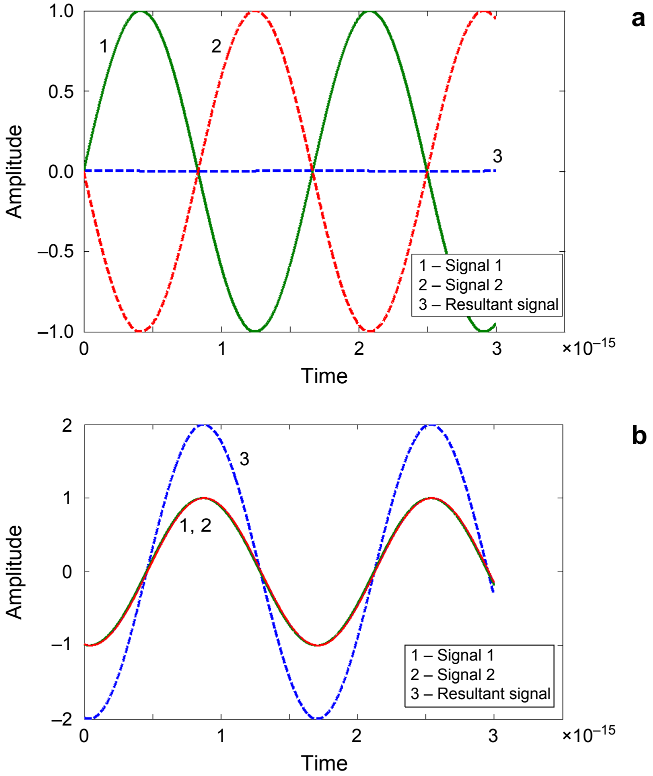

Fig. 9. Perfect destructive interference by 500.000001 nm (**a**) and perfect constructive interference by wavelength 500.0004500 nm (**b**); L_1 and L_2 are 150 and 160 μm, respectively.

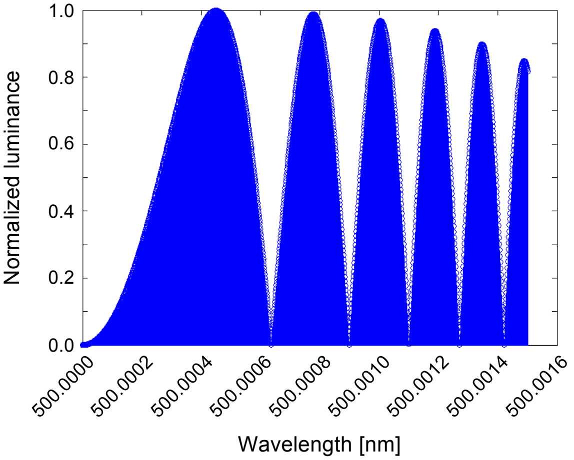

Fig. 10. Luminance as a function of wavelength (500.0000 to 500.0015 nm).

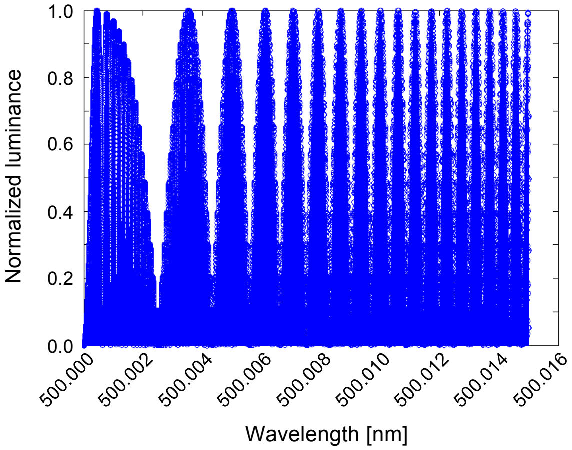

Fig. 11. Luminance wavelength diagram for 500.000 to 500.015 nm.

By considering Fig. 11, it looks as if the intensity of the interference pattern is a magnitude of a sinusoid function carried by a higher frequency in an AM shape. Also, one can see that the intensity of light is a periodic function with a variable frequency. By increasing the optical wavelength, the frequency of intensity changes increases and hence we can say that the wavelength is carried by the frequency of output intensity changes.

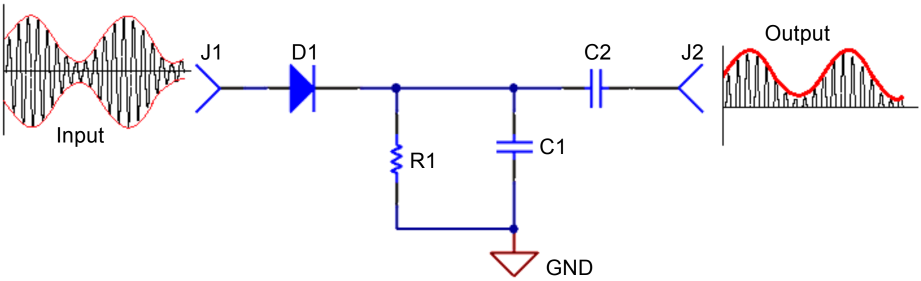

Fig. 12. AM detector circuit to detect wavelength changes in photodiode current.

The wavelength changes will cause an AM shape on photodiode current. To complete the sensor configuration, it is important to use an AM detector circuit after photodiode to obtain a reliable sinusoidal function on the output, as shown in Fig. 12.

4. Conclusion

Based on the device suggested in this paper, we are able to design and implement new high efficiency optical modulations used in optical communications and combine them with other modulations to obtain a higher data transferring rate. Also, we are able to detect and amplify small changes in wavelength and frequency of a beam for high accuracy applications such as investigating wavelength stability of a laser beam. Also, in this device, the analog-to-digital convertor at the transmitter and digital-to-analog convertor at the receiver are removed. In other words, the suggested structure is simpler and more commercial in optical communications and applications.

References

[1] DUTTON H.J.R., *Understanding Optical Communications*, IBM Corporation, 1998, pp. 256–257.

[2] TIANTIAN LI, JUNLONG ZHANG, HUAXIANG YI, WEI TAN, QIFENG LONG, ZHIPING ZHOU, XINGJUN WANG, HEQUAN WU, *Low-voltage, high speed, compact silicon modulator for BPSK modulation*, Optics Express **21**(20), 2013, pp. 23410–23415.

[3] KITA T., NEMOTO K., YAMADA H., *Narrow spectral linewidth and high output power Si photonic wavelength tunable laser diode*, IEEE 10th International Conference on Group IV Photonics (GFP), 2013, pp. 152–153.

[4] EL-TAHER A.E., HARPER P., BABIN S.A., TURITSYN S.K., *High-power widely tunable Raman fiber laser*, Lasers and Electro-Optics Europe (CLEO EUROPE/IQEC), 2013 Conference on and International Quantum Electronics Conference, p. 1.

[5] LI S.G., GONG Q., LAO Y.F., ZHANG Y.G., FENG S.L., WANG H.L., *InAs/InP(100) quantum dot laser with high wavelength stability*, Electronics Letters **46**(2), 2010, pp. 158–159.

[6] RYVKIN B., AVRUTIN E., *Narrow asymmetric waveguide semiconductor lasers with improved temperature wavelength stability for pumping and nonlinear applications*, 11th International Conference on Transparent Optical Networks, ICTON'09, 2009, pp. 1–4.

[7] RONGQING HUI, O'SULLIVAN M., *Fiber Optic Measurement Techniques*, Elsevier Academic Press, 2009.

[8] MALAK M., MARTY F., NOUIRA H., SALGADO J., BOUROUINA T., *All-silicon interferometric optical probe for non-contact dimensional measurements in confined environments*, 2012 IEEE 25th International Conference on Micro Electro Mechanical Systems (MEMS), 2012, pp. 628–631.

[9] *InGaAs Photodiodes: Near Infrared Detectors with Low Noise and Superb Frequency Characteristics*, Hamamatsu Photonics K.K., http://www.hamamatsu.com/resources/pdf/ssd/ingaas_kird0005e.pdf

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