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SELF-MIXING IN A DIODE LASER AS A METHOD FOR COHERENT PHOTODETECTION

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Abstract. The measurements described in this paper are based on the self-mixing that occurs in the diode laser cavity when radiation is reflected by the moving target into the laser, interferes with the field inside it and causes changes in the laser pump current. The self-mixing signal is extracted by two different ways simultaneously: by the help of a photodiode accommodated in the rear facet of the diode laser package, commonly used for monitoring the laser power, and by the help of a small resistance resistor in the laser pump circuit. A special low-noise two-channel amplifier was designed and built.

As compared to conventional interference methods, the self-mixing method described has the same sensitivity, but it has substantial advantages, such as simplicity, compactness, and robustness as well as self-aligning and self-detecting abilities.

This method of optical self-mixing in a diode laser allowed for the measurement of arterial pulsatility in medicine. The system enabled us to detect pulsation profiles of major arteries with potentially useful information, including pulse wave velocity and profile.

Key words: self-mixing, diode laser, coherent photodetection, arterial pulsatility, pulse wave velocity, pulse wave profile.

1. INTRODUCTION

Though well known, it is only until recently that coherent photodetection has found a wide application. Complicated technical problems arise when mixing different optical waves, particularly in the visible region of the optical band. Moreover, high quality optics is expensive. Discussions concerning methods of coherent photodetection have continued for a long time and during the last years new developments have taken place. These are based on the fact that coherent receiving enables one to acquire more information during measurements inside the optical band.

The coherent photodetection of the radiation reflected back from the object surface is used in measuring vibrations [1], deformations [2], and distances [3]. The method of coherent photodetection is used in several biomedical applications as coherent image detection [4], Doppler interferometry [5], Doppler anemometry [6], and in different sensors [7].

These are examples of the application of coherent photodetection. However, realizations are technically complicated and carefully aligned high-quality optics is needed. Conventionally, as in a classical heterodyne interferometer, the optical coherent beam radiated from the laser is divided into two components of the same amplitude: a reference beam and a signal beam. After reflecting on the mirror and passing the beam splitter, the signal beam interferes with the reference beam on the photodetector and a beat signal with the heterodyne frequency is generated. In that design, optical components, such as a beam splitter, a mirror, and a photodetector are needed in addition to the light source.

In this study, efforts have been focused on the development of a novel principle of coherent detection based on mixing and synchronization inside the laser active medium to realize more simple and effective methods for coherent receiving, including visible optical region. These methods enable us to simplify the optical scheme of such devices and achieve the mixing effect where a small portion of the light reflected from the mirror is returned into the laser cavity and is mixed with the original oscillating wave inside the laser. This method of coherent photodetection inside the laser cavity leads to the design without beam splitters and external photodetector, providing significant advantages because of ease of alignment.

In medical applications, this method allows an optical no-touch measurement of skin surface vibrations, which can reveal the pulsatile propagation of blood pressure waves along the vasculature. Typically, vessel wall expansion and shrinkage results in the movement on the skin surface, containing such useful parameters as the period of pulsation, blood pressure and pulsation profile. Because the method of self-mixing requires only one optical axis to be considered and is self-aligning and self-detecting, in addition to the use of fewer optical components it provides substantial advantages in compactness, simplicity and ease of alignment over the conventional methods. In particular, in fibre-coupled systems, this method provides a simpler optical arrangement and a comparatively high signal-to-noise ratio.

We designed a laser Doppler device based on the self-mixing effect in a fibre-coupled semiconductor laser. The laser light is coupled into a fibre and guided towards a moving object. A small part of the Doppler-shifted light reflected by the moving object is collected by the same fibre and guided back into the laser. The Doppler-shifted light interferes with the laser light present in the laser cavity and causes an intensity modulation of the laser. The frequency of this intensity modulation is related to the Doppler shift. This device may be used in different medical applications for vibration measurements.

2. PRINCIPLES OF OPERATION

To date, various theoretical models have been used to explain the observed phenomena in the self-mixing process [8–10], but the modulation mechanism of external optical feedback in the laser output is not well understood yet. It is obvious that some phenomena observed with external optical feedback are dramatically different from those of conventional interferometry, and they cannot be explained simply by using the existing coherent interference theory. In biomedical applications, the effects of external optical feedback are widely used, for example, to detect small moving micron-size particles [11,12].

In general, self-mixing can be regarded as a simplified external cavity laser, as shown schematically in Fig. 1, where the surface of the external reflector $R3$ and one of the laser facets, $R2$, constitute an effective laser mirror $R2'$, the power reflectivity of which can be expressed as

$$R2' = R2\,[1 + \xi^2 + 2\xi \cos(2\pi L/\lambda)], \qquad (2.1)$$

where $R2$ is the power reflectivity of the laser facet, $\xi = R3/R2$ is the ratio of the amplitude reflectivity of the external reflector (including the geometric loss and the feedback-coupling efficiency) to the laser-facet amplitude reflectivity, here termed the feedback coefficient, L is the optical distance between the laser and the external reflector, and λ is the lasing wavelength of the laser.

When a single-mode laser is operated above its threshold, without considering the external feedback, the total emitted power P_0 from the laser facets, caused by stimulated emission, can be given by [13]

$$P_0 = (h\nu)\,(c/n)\,(S/2l)\,\ln(1/R1R2), \qquad (2.2)$$

where h is the Planck constant, ν is the optical frequency of the laser, c is the velocity of light, n is the effective refractive index of the laser cavity, S represents the photon number in the laser cavity caused by stimulated emission, l is the cavity length, $R1$ and $R2$ are the power reflectivities of the laser mirrors, respectively.

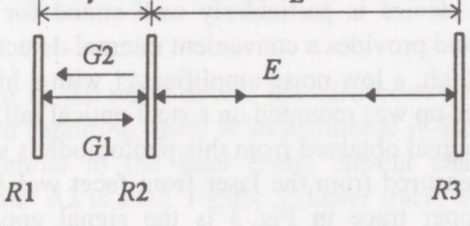


Fig. 1. Schematic of a simple laser with external optical feedback: l – laser-cavity length; L – distance from laser-cavity front face to target; E – electric field; $G1$, $G2$ – forward and backward gain in the laser cavity; $R1$, $R2$ – laser mirrors; $R3$ – the target.

The presence of the external cavity changes the effective reflectivity of the laser mirror according to Eq. (2.1), and therefore changes the emitting power of the laser. The substitution of Eq. (2.1) into Eq. (2.2) under the assumption of weak optical feedback results in an emitting power from the laser, expressed as

$$P \approx P_0\,[1 + \zeta \cos(2\pi L/\lambda)], \tag{2.3}$$

where $\zeta = 2\xi/\ln(R1\,R2)$ is related to the feedback coefficient ξ and the power reflectivity of the laser facets, which is referred to here as the modulation coefficient.

It is clear that the modulation term in the relation (2.3) is dependent on the feedback strength and on the distance of the external reflector; it is a repetitive function (corresponding to a variation of the displacement $\lambda/2$ at the external reflector). This simple model, based on the threshold modulation, explains well our experimental results. However, the effect of the external optical feedback does not only change the threshold but also the laser spectrum. Therefore, a detailed theoretical analysis should consider both the variations of the threshold and the spectrum of the laser oscillation.

3. EXPERIMENT

3.1. Self-mixing in a diode laser

The experimental scheme used to investigate the effects of self-mixing in a diode laser is shown in Fig. 2. In this scheme, the light from the buried heterojunction InGaAs laser diode (Philips CQF-56 with a thermoelectrical cooling system) with the wavelength of 1310 nm and with output optical power of 2 mW was collimated and focused by a lens on the target, which is represented by a reflective surface attached to a loudspeaker cone driven by a signal generator, to provide phase variations of the external optical feedback.

The diode laser incorporates a photodiode accommodated in the rear facet of the laser and normally used for monitoring the laser output optical power. This characteristic of the device is particularly well suited for observing the self-mixing interference and provides a convenient internal detector. Since the signal-source resistance is high, a low noise amplifier $A1$ with a high input impedance is used. The whole set-up was mounted on a steel optical rail.

A typical output signal obtained from this photodiode is shown in Fig. 3. The feedback strength measured from the laser front facet was less than 10% in all experiments. The upper trace in Fig. 3 is the signal applied to achieve the periodic target movement, and the resultant intensity modulation (middle trace) is the self-mixing signal observed.

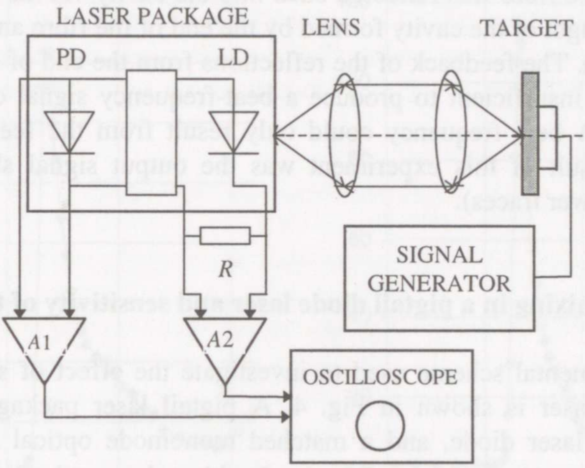


Fig. 2. Schematic experimental arrangement: PD – photodiode (integral); LD – laser diode; *A*1, *A*2 – amplifiers; *R* – resistor.

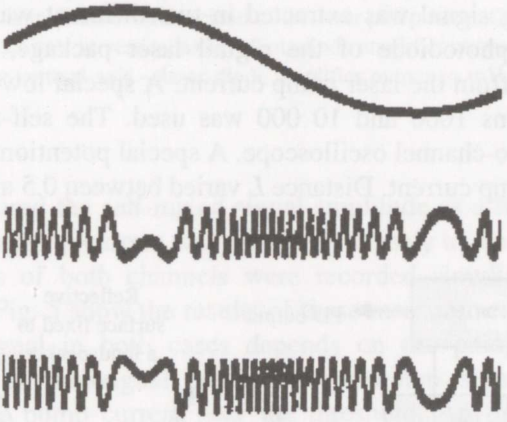


Fig. 3. Typical signals observed by self-mixing: upper trace – signal applied to achieve the periodic target movement; middle and lower traces – self-mixing signals from amplifiers *A*1 and *A*2.

Another structure of the same device has also been under observation. For signal separation and capturing, there is an additional resistor *R* ($R = 50\ \Omega$) with an intermittent potential in the laser pump current chain. To amplify this potential, the amplifier *A*2 is used. Figure 3 (lower trace) shows the self-mixing signal observed in this case.

For further investigation we used a monomode fibre of 1 m in length with the core diameter of 9 µm. The same experimental scheme was used, and the light emitted from the fibre was reflected back into the cavity via the same fibre. The geometrical length of the cavity formed by the end of the fibre and the target was typically 1 mm. The feedback of the reflections from the end of the fibre closest to the laser is insufficient to produce a beat-frequency signal due to a special construction. A beat frequency could only result from the feedback from the target. The result of this experiment was the output signal shown in Fig. 3 (middle and lower traces).

3.2. Self-mixing in a pigtail diode laser and sensitivity of the method

The experimental scheme used to investigate the effect of self-mixing with pigtail diode laser is shown in Fig. 4. A pigtail laser package consists of a photodiode, a laser diode, and a matched monomode optical fibre of 1 m in length with its core diameter of 9 μm. In this scheme, the light from pigtail heterojunction InGaAs laser diode Philips QF 4142 with the wavelength of 1310 nm, the threshold current of 24 mA, and with output optical power 0.2 mW was emitted from the fibre output and reflected back to the fibre and via fibre into the laser cavity by a mirror, fixed to the loudspeaker cone.

The self-mixing signal was extracted in two different ways simultaneously: with the built-in photodiode of the pigtail laser package, and with a small resistance resistor from the laser pump current. A special low-noise two-channel amplifier with gains 1000 and 10 000 was used. The self-mixing signal was recorded with a two-channel oscilloscope. A special potentiometer *P* was used to adjust the laser pump current. Distance *L* varied between 0.5 and 42 mm.

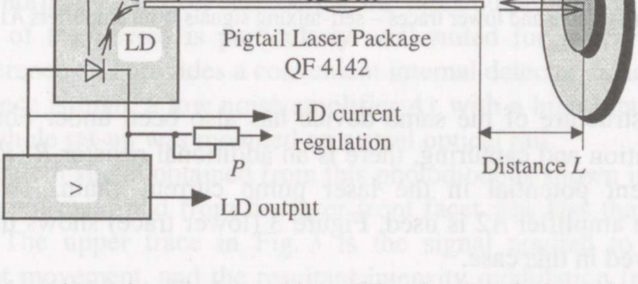
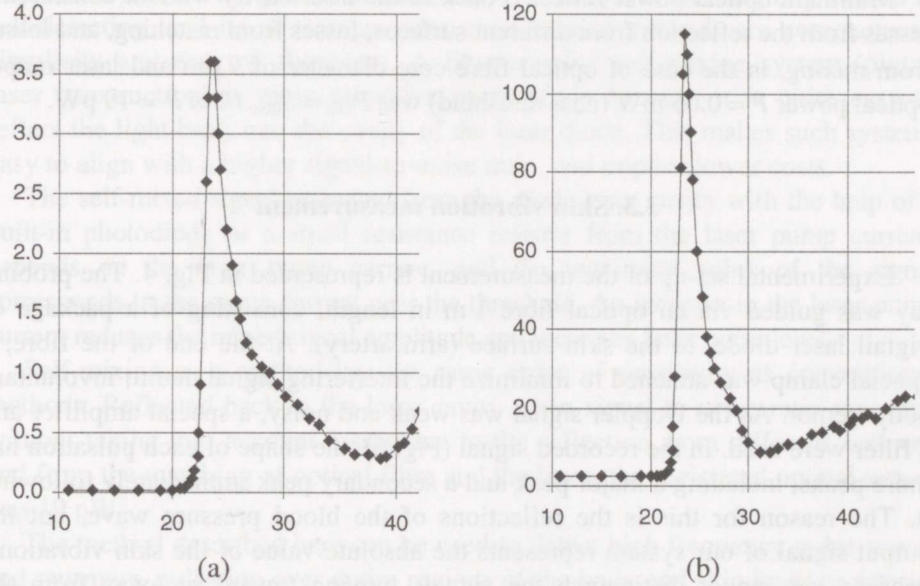


Fig. 4. Schematic experimental arrangement with amplifiers for photodiode and laser diode output signals and with laser diode pump current regulation.



(a) (b)

Fig. 5. Self-mixing signal amplitude dependent on the laser pump current in the photodiode output and in the laser diode chain (resistor in the chain of the laser pump current). QF 4142 laser with the threshold current I_{th} = 24 mA. a: vertical axis – photodiode amplifier output in V, horizontal axis – laser current in mA; b: vertical axis – laser diode amplifier output in mV, horizontal axis – laser current in mA.

First, we measured the self-mixed signal amplitude as a function of the laser pump current. The pump current was adjusted precisely to the potentiometer, and the output signals of both channels were recorded simultaneously. The two characteristics in Fig. 5 show the results of these measurements. As can be seen, the self-mixed signal in both cases depends on the pump current, and the maximum value of the signal (with the maximum signal to noise ratio) corresponds to the pump current near the threshold. An increase in the laser pump current reduces the mixed signal amplitude and raises the noise level of the laser.

Secondly, we measured the sensitivity of self-mixing. We registered maximum distance $L_{\max}$ = 42 mm (distance from the optical fibre output to the target) when the self-mixed signal amplitude in the amplifier output was equal to noise (signal to noise ratio was 1). This situation corresponds to the minimum of the reflected signal which can be measured without additional signal processing. Then we calculated the amount of the radiation reflected back from the target to optical fibre input in the case of $L_{\max}$. The measured optical radiation radiated from the fibre was the same in both plane surfaces, and the calculated spatial angle for 90% of radiation was 10 deg. The calculated surface of the reflected radiation in the surface of the optical fibre was 168 mm^2.

Minimum optical power reflected back to the laser cavity without considering losses from the reflection from different surfaces, losses from matching, and losses from mixing, in the case of optical fibre core diameter of 9 μm and laser output optical power $P = 0.05$ mW (near threshold) was $P_{\min} = S_{\text{fibre}} / S \times P = 19$ pW.

3.3. Skin vibration measurement

Experimental set-up of the measurement is represented in Fig. 4. The probing ray was guided via an optical fibre 1 m in length, consisting of a package of pigtail laser diode, to the skin surface (arm artery). At the end of the fibre, a special clamp was attached to minimize the interfering signal due to involuntary body tremor. As the Doppler signal was weak and noisy, a special amplifier and a filter were used. In the recorded signal (Fig. 6), the shape of each pulsation has more peaks, including a major peak and a secondary peak immediately following it. The reason for this is the reflections of the blood pressure wave, but the output signal of our system represents the absolute value of the skin vibrations, because we cannot distinguish the signals moving toward or away from the probing ray.

To register skin vibrations, we used a special National Instruments data acquisition board (DAQ) AT-M10-16E-10 to digitize signals locally and to transmit the digital data to the PC via the parallel port with the maximum sampling rate 100 kHz and resolution 12 bits. The 133 MHz Pentium PC with National Instruments software LabVIEW for Windows was applied. Between PC and DAQ, a special block of digital filters was used to find an algorithm for calculating the optimal signal to noise ratio fast.

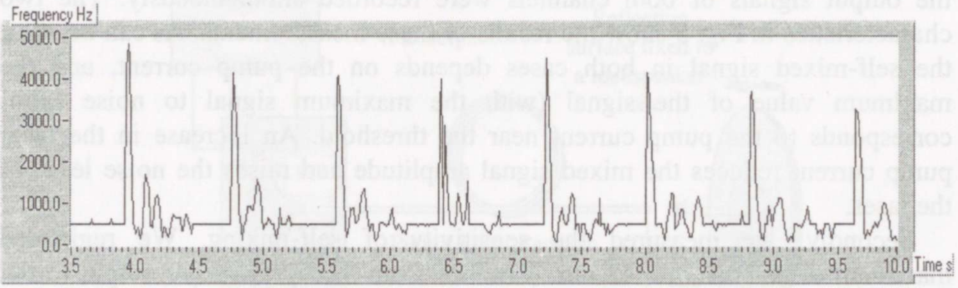


Fig. 6. Measured skin vibration profile on the arm artery.

4. CONCLUSIONS

Self-mixing in a laser cavity, as a new method for coherent photodetection, is simpler than conventional methods. It requires only one optical axis to be considered and fewer optical components. This method is self-aligning as well as self-detecting, and its advantages over conventional methods are compactness, simplicity and ease of alignment. A fiber-coupled self-mixing system (pigtail laser construction) is more attractive, particularly because it is quite easy to reflect the light back into the cavity of the laser diode. This makes such systems easy to align with a higher signal-to-noise ratio, and implies lower costs.

The self-mixed signal extracted from the diode laser cavity with the help of a built-in photodiode or a small resistance resistor from the laser pump current, depends on the laser pump current, and the maximum value of the signal corresponds to the pump current near the threshold. An increase in the laser pump current reduces the mixed signal amplitude and increases laser noise level.

Self-mixing as a method has the same order of sensitivity as conventional methods. Reflected back to the laser cavity when signal to noise ratio was one, without taking into account losses due to the reflection from different surfaces and from the matching of optical fibre and the laser, the registered optical power was 19 pW.

The method described here can be used to detect high frequency pulse waves and murmurs, pulsation over entire regions of the body and skin layer or arterial wall movements with different penetration depth, depending on the used laser wavelength.

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ISESEGUSTAMINE DIOODLASERIS KUI MEETOD KOHERENTSEKS FOTODETEKTEERIMISEKS

Kalju MEIGAS, Hiie HINRIKUS, Jaanus LASS ja Rain KATTAI

Artiklis vaadeldakse isesegustamist, mis leiab aset pooljuhtlaseri resonaatoris, kui liikuvalt objektilt laserisse tagasi peegeldunud kiirgus seguneb laseri kiirgusega, põhjustades muutusi laseri ergutusvoolus. Isesegustamissignaal on eraldatud samaaegselt kahel viisil: 1) kasutades fotodioodi, mis paikneb pooljuhtlaseri korpuses ja mida tavaliselt kasutatakse laseri optilise väljundvõimsuse mõõtmiseks, 2) väikese takistusega takisti abil, mis paikneb laseri ergutusvoolu ahelas. Isesegustamissignaali eraldamiseks väljundis optilist kiudu omavas pooljuhtlaseris on projekteeritud ja valmistatud kahekanaliline väikese müraga võimendi.

Automaatse detekteerimise ja justeerimise tõttu on kirjeldatud meetod tunduvalt lihtsam ja kompaktsem kui tavalised interferentsmeetodid, samal ajal kui meetodi tundlikkus on nendega võrreldav.

Isesegustamismeetodi abil on mõõdetud inimese arteri pulseerimist ja registreeritud pulsilaine kuju. Mõõtes veresoonte pulseerimist keha mitmetes punktides saab leida ka pulsilaine levimise kiiruse.