Optoelectronic Chromatic Dispersion in Germanium PN Photodiodes

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Introduction

The dependence of photodiode efficiency and RF bandwidth on the wavelength is well known. However, this wavelength dependency leads to a prominent feature of photodiodes that has been largely overlooked. The wavelength-dependent pathlength of the migrating charge-carriers is the source of an extremely large effective chromatic dispersion. Based on this inherent feature, we regard this device as a source of optoelectronic chromatic dispersion (OED). In this work we demonstrate the potential applications for a sensor based on photodiode OED.

OED Theory

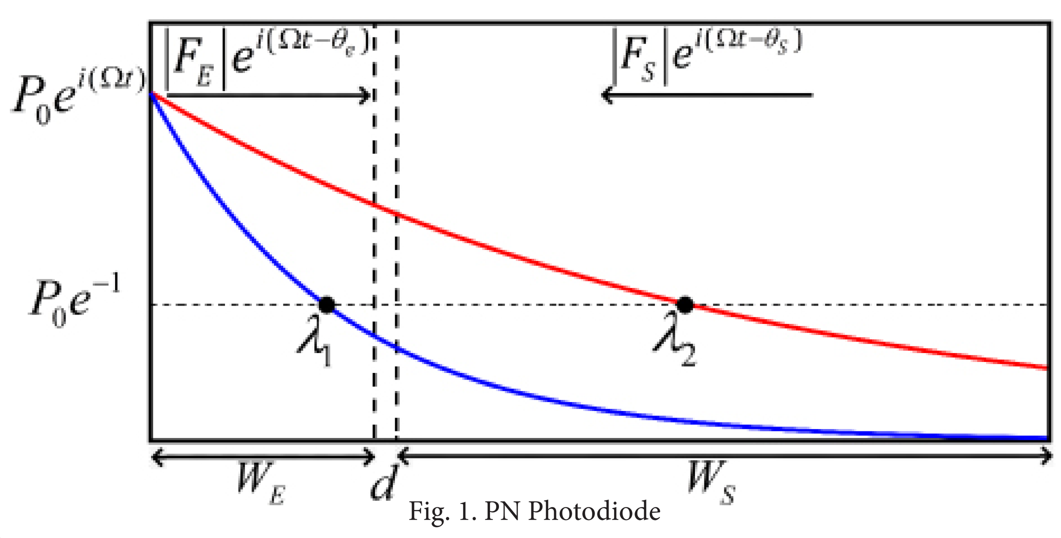

Fig. 1. PN Photodiode

Sinusoidal-modulated light with wavelengths λ_1, λ_2 and power $P_0 e^{i(\Omega t)}$ illuminats a PN photodiode. Absorption, charge-pair formation, and subsequent diffusion leads to a measurable modulated current. Current contribution in each region leads to a total current at frequency Ω that is proportional to the sum of these terms:

$$F_{tot} = |F_E| e^{-i\theta_E} + |F_S| e^{-i\theta_S} = |F_{tot}| e^{-i\theta_{tot}}$$

where E, S refer to entrance and substrate, respectively. The amplitudes and phases of these terms are dependent upon several parameters, but, crucially, there is a wavelength dependence through the absorption spectrum $\alpha(\omega)$ and a dependence on the modulation frequency $\Omega = 2\pi f$. Referring to fig. 1, if wavelength λ_2 increases to $\lambda_2 = \lambda_2 + \delta\lambda$, the penetration depth recedes from the junction, the average diffusion time of the charge carriers increases, and so does the modulation phase-shift delay. The opposite will happen if wavelength λ_1 increases, the average diffusion time will decrease and so will the modulation phase-shift delay.

The sensitivity of such a sensor can be defined as change of phase relative to change in wavelength

$$S_{OED} \equiv d\theta_{tot} / d\lambda$$

Experimental Setup and OED Characterization

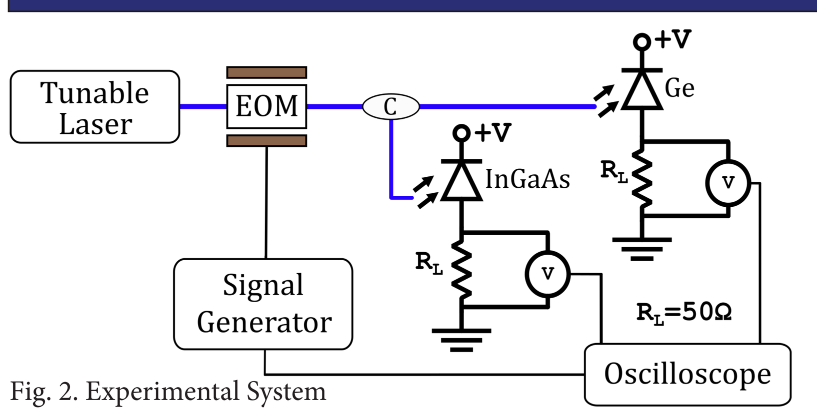

Fig. 2. Experimental System

The system is shown in fig. 2 and consists of a tunable laser source in the C-band, a Mach-Zehnder modulator and two photodiode circuits – one with a PN-type Ge photodiode which exhibits OED, the other with a PIN-type InGaAs photodiode, which does not.

The photodiodes are operated in the reverse bias regime, and the voltage resulting from the photodiode's current is measured on a 50Ω load resistor. The PIN-type InGaAs photodiode, served as a reference signal. In general, PIN-type photodiodes have a large intrinsic layer, which is usually dominant compared to the relatively small entrance and substrate regions, which leads to a negligible OED in the C-band. The tunable laser was set to a starting wavelength of 1550nm and was swept up to 1568nm with a step of 2 nm. At each wavelength, the modulation frequency was scanned in the range between 1 kHz and 12 MHz.

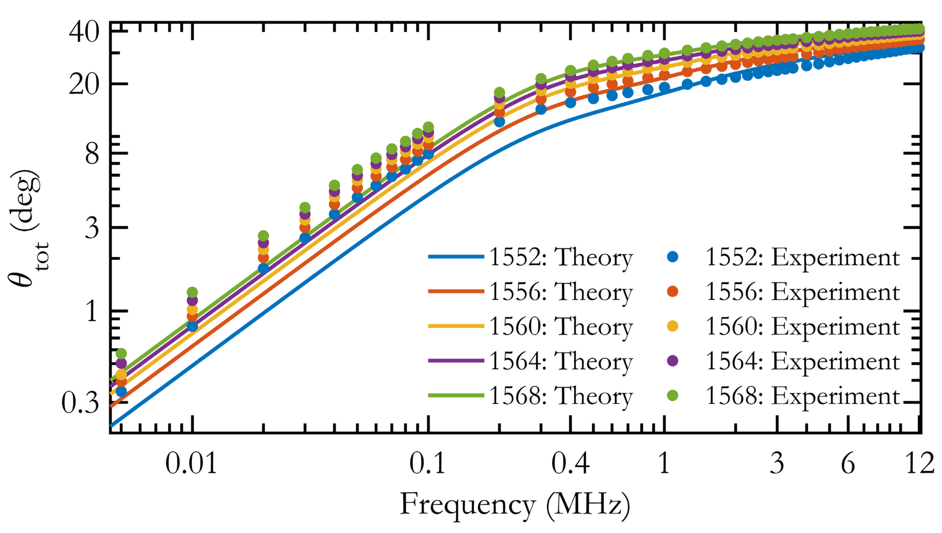

Fig. 3. Phase θ_{tot} as a function of signal modulation frequency and wavelength

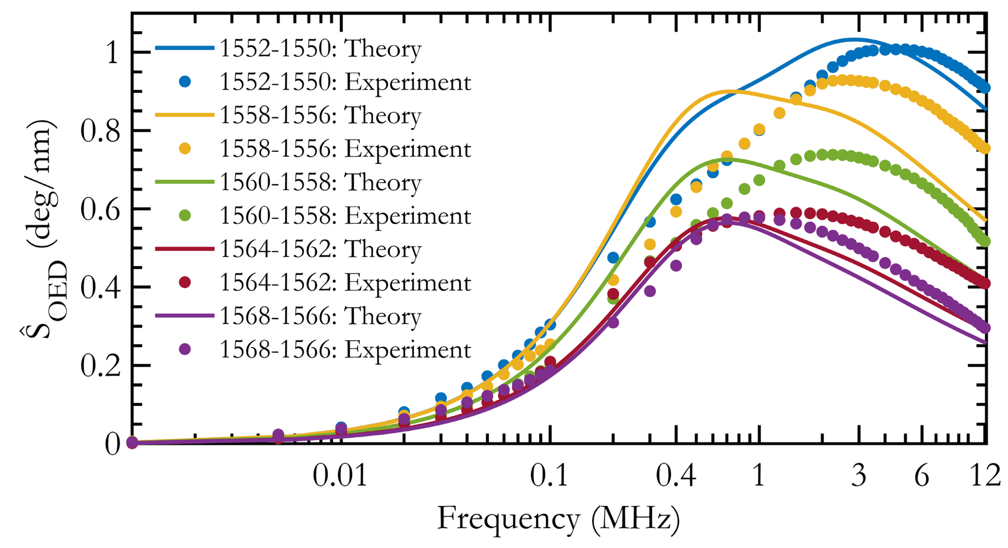

Fig. 4. S_{OED} as a function of modulation frequency for five pairs of wavelengths.

Fig. 3 displays the predicted and measured phase dependence on frequency for several wavelengths. The phase initially increases linearly with frequency, and then plateaus at higher frequencies. By subtracting two phase curves, a sensitivity as a function of modulating frequency and light wavelength can be extracted (fig. 4)

Application in Wavelength Monitoring

The sensitivity of OED was enhanced by utilizing a technique called phase-shift amplification by RF interferometry (PARFI). This allows for amplification of the RF phase-shift produced by OED to enhance the resolution.

The phase-amplified OED system is shown in fig. 6. Light from a tunable laser is intensity modulated and detected by a reverse-biased Germanium PN photodiode. The OED signal is then combined with a reference signal in an RF coupler in order to form PARFI.

The OED sensitivity for 1 pm steps of the laser is only 670 μdeg/pm, which is challenging to measure. The experimental results of PARFI amplified OED are presented in fig. 8, where two amplification factors are shown - $G = 4 \cdot 10^4$ and $G = 1.8 \cdot 10^3$.

After amplification by PARFI, we achieved a normalized wavelength sensitivity of $\Delta\lambda_{min} = 1$ fm

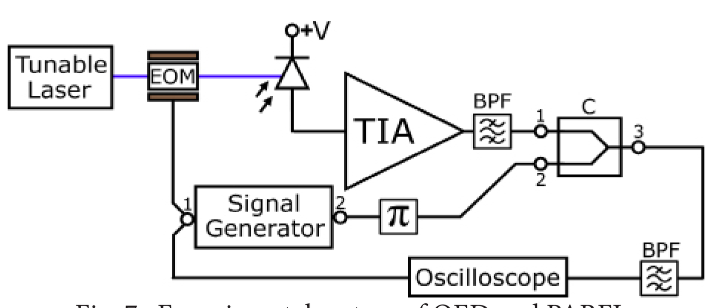

Fig. 7. Experimental system of OED and PARFI.

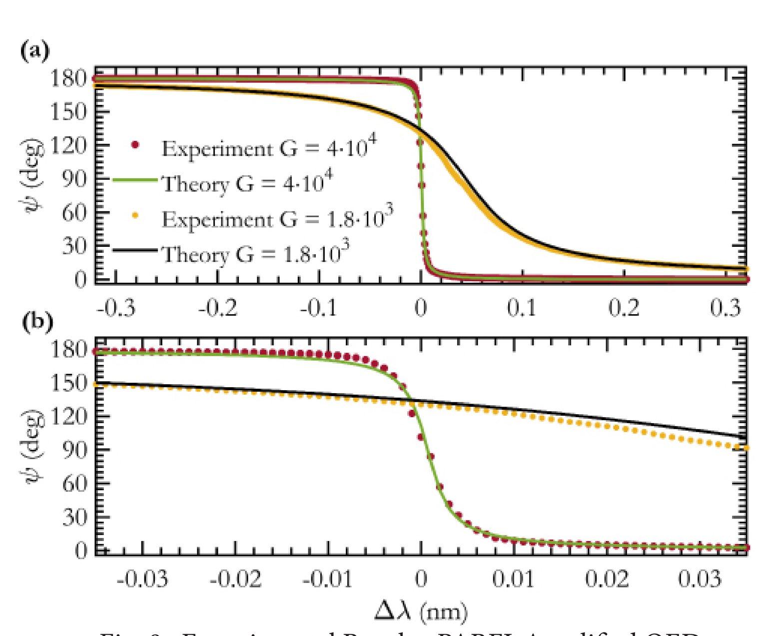

Fig. 8. Experimental Results: PARFI-Amplified OED

For further reading on PARFI and PAI:

Application in FBG Interrogation

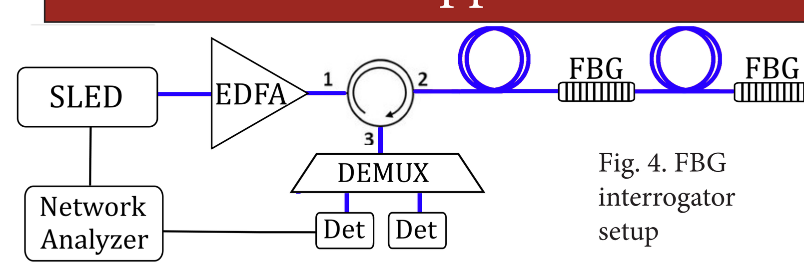

Fig. 4. FBG interrogator setup

The OED effect was integrated into an FBG interrogator system which utilizes the RF phase-shift method and OED to monitor wavelength shifts.

Fig. 4 depicts the interrogation setup. A directly modulated superluminescent diode (SLED) in the C-band provides a broadband (30 nm spectral-width) sinusoidal-modulated optical signal, which is then sent through a series of FBG sensors. This technique allows simultaneous interrogation of all the sensors. The reflected light of each sensor is diverted onto a Ge photodiode.

Then A constant sinusoidal vibration at a frequency of 17.9 kHz was applied on one of the FBG sensors. The results after FFT processing are presented in fig. 5. Fig. 6 shows a reconstructed signal after performing IFFT.

The measured normalized sensitivity was 1.474pm/$\sqrt{\text{Hz}}$

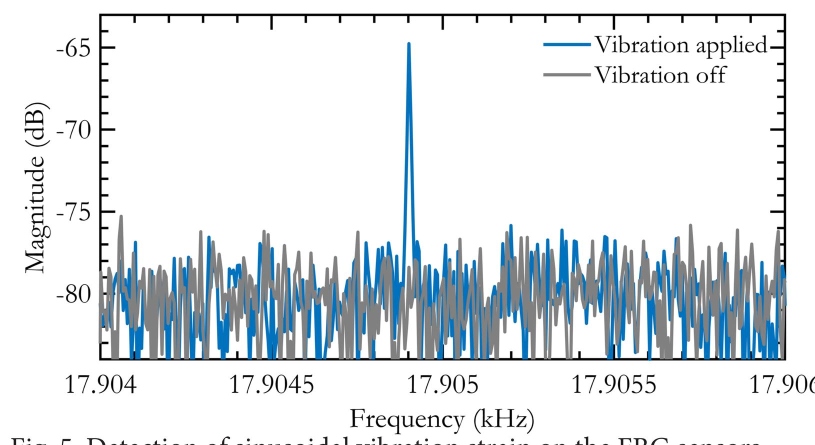

Fig. 5. Detection of sinusoidal vibration strain on the FBG sensors.

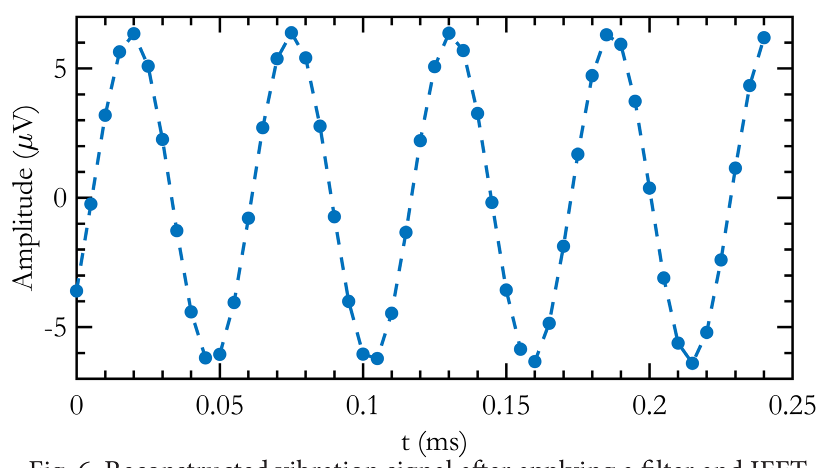

Fig. 6. Reconstructed vibration signal after applying a filter and IFFT.

Application in Spectral Sensing

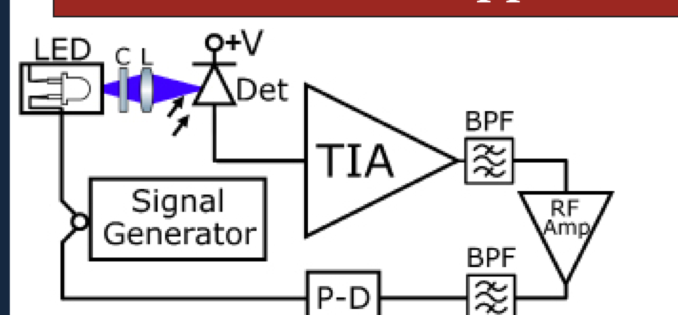

Fig. 9. Spectral Sensing Setup

In this work we present a spectral sensor based on OED in a Ge PN photodiode, with high potential for low-cost on-chip implementation. Using a wideband light emitting diode (LED) and a Ge PN photodiode (fig. 9), we demonstrate 70 ppm (0.007%) resolution of alcohol content in water.

When the PD is illuminated by a spectrally wideband light source, the total OED output signal is comprised of a summation of phasors: $F_{tot} e^{-i\theta_{OED}} = \sum_{\lambda_1}^{\lambda_N} |F_\lambda| e^{-i\theta_\lambda}$ each with an amplitude that is dependent upon the power of the particular wavelength component of the illumination, as well as its corresponding absorption in the medium, and a phase which is the OED phase contribution of the wavelength component.

When the spectral composition of the light is altered, for example, due to absorption in a medium under test, a shift of the total phase at the output of the photodiode can be measured.

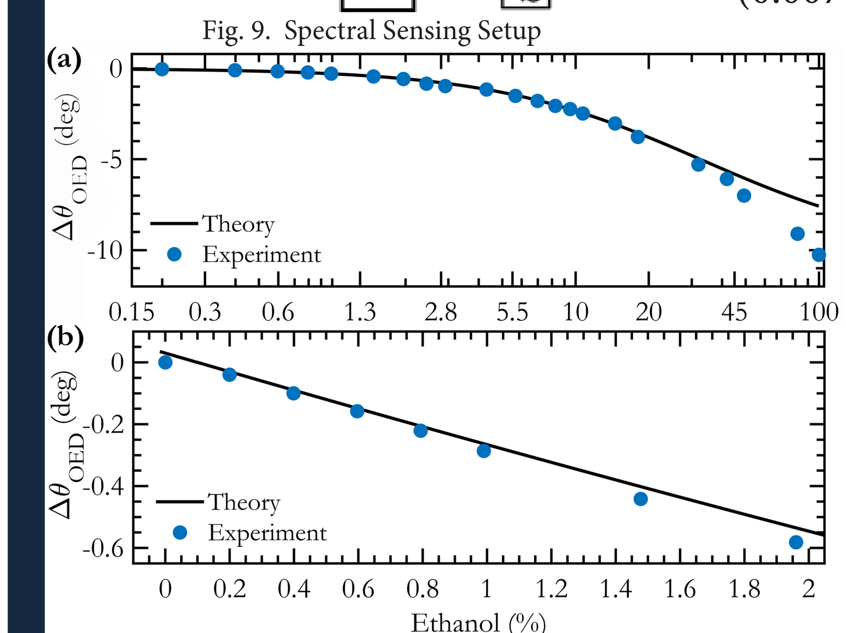

Fig. 10. Experimental results. (a) full range 0-100% ethanol concentration, (b) zoom-in over the range 0-2%.

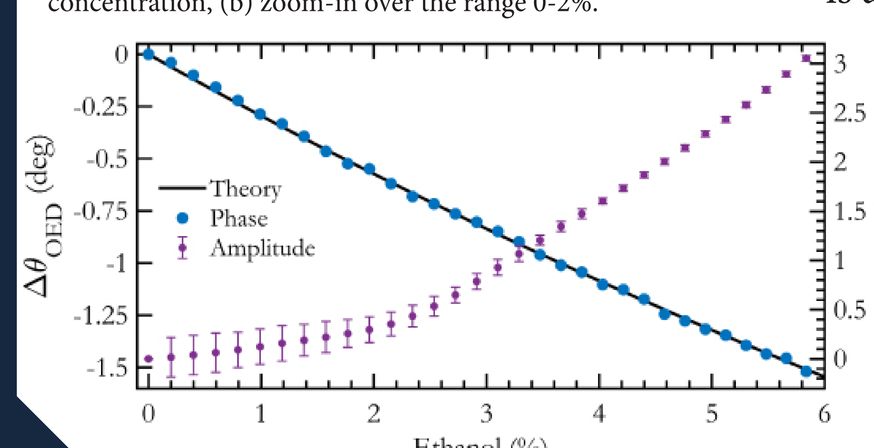

Fig. 11. Step-to-step changes in relative amplitude and phase for low concentration changes of ethanol in water.