Towards Integrated Optical Feedback FM-to-AM Conversion in Silicon Nitride for Displacement Sensing Applications

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***Abstract*—In this paper, we demonstrate the potential of silicon nitride integrated edge filters to perform frequency to amplitude (FM-to-AM) conversion of optical feedback interferometric (OFI) signals to achieve better signal-to-noise ratio than the typical AM OFI signals. Compared to already existing OFI FM-to-AM conversion techniques such as edge filters based on gas cells, and free-space or fiber Mach Zehnder interferometer (MZI), integrated photonic processing of OFI signals can offer greater compactness and design flexibility. In addition, compactness can also indirectly improve noise performances by facilitating temperature control of the chip and allowing a higher immunity to parasitic mechanical vibrations. The FM OFI detection is performed with an integrated MZI with a 2 cm imbalanced path-length implemented on a silicon nitride process. The achieved OFI FM-to-AM conversion factor is 0.83 (GHz)$^{-1}$ and the noise equivalent displacement is 16 nm for a 1 kHz bandwidth.**

***Keywords*—Mach Zehnder interferometer; self-mixing; optical feedback interferometry; laser sensors; silicon nitride; integrated photonics**

I. Introduction

Optical feedback interferometry (OFI), also referred as the self-mixing (SM) effect in laser diodes (LDs), has been widely investigated in recent decades as it results in a self-aligned and cost-effective sensing system for displacement, vibration or velocity measurements for instance [1], [2]. The resolution of OFI-based displacement sensors depends on the employed signal processing techniques [3]–[6].

In OFI, a portion of the laser beam can be backscattered from a target placed away from the laser and can thus re-enter the active laser cavity. This directly affects the optical fields within the LD cavity. It results in the modulation of both amplitude (AM) and frequency (FM) of the optical field (see Fig. 1 a)) as described by Lang and Kobayashi equations [7]. The OFI information embedded in the optical power modulation (and thus AM channel) is usually preferred to the FM channel as it is directly available by the LD monitoring photodiode or simply by monitoring a fraction of the optical

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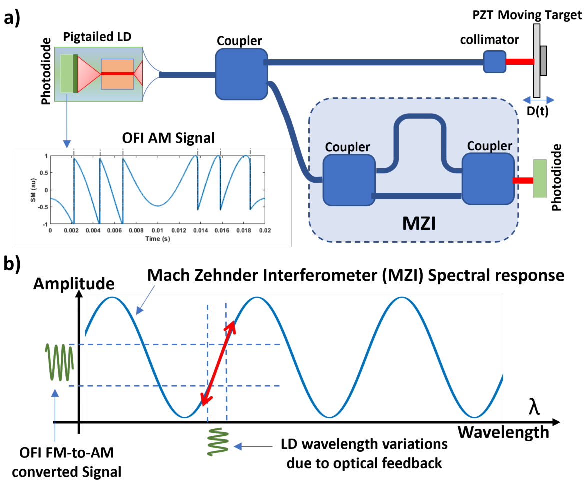

Fig. 1. a) Typical Fiber OFI sensing setup using a laser diode and a piezotransducer (PZT) as a target, showing in particular the AM channel retrieved from the monitoring photodiode. b) OFI frequency modulation (FM) signal embedded in the laser frequency is converted into amplitude modulation (AM) by using the fringe edge of a Mach Zehnder interferometer (MZI) used as an optical filter.

power emitted by the LD. However, it was shown in [8] that the SNR of FM OFI signals is approximately two orders of magnitude better than the AM one. As a result, FM OFI signals are thus of utmost importance to enhance OFI sensitivity not only for low-noise small displacement applications but also for non-cooperative diffusive remote target surfaces resulting in low back-scattered OFI signal.

Recently, OFI FM-to-AM conversion has been achieved using the edge of optical filters. The conversion principle is illustrated in Fig.1 b). In [9], an acetylene gas cell is used as the converting filter. The steep edge of an optical absorption profile of the cell provides an OFI FM-to-AM conversion factor of approximately 2.2 (GHz)$^{-1}$ with a typical absorption line depth of 8 dB. To improve further both the sensitivity and the flexibility of the filter, other approaches have then

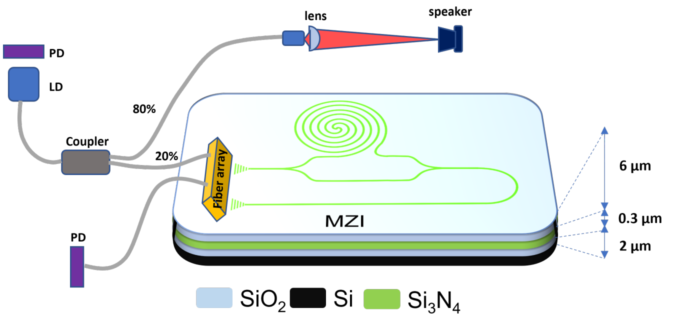

Fig. 2. Schematic diagram of one of the three OFI FM-to-AM optical feedback interferometry systems that includes one laser diode (LD), two photodiodes (PD), one fiber array, the Integrated Photonic OFI FM-to-AM filter based on a Mach Zehnder interferometer (MZI) and a speaker as remote target.

emerged based on free-space and fiber-based Mach Zehnder interferometers (MZI) [8], [10]. As a result, the LD wavelength can be more easily tuned to one of the periodic signatures of the MZI. In addition, the sensitivity related to the steepness of the response can also be adjusted via the optical path length imbalance between the two MZI arms. The achieved sensitivity is 19 $(\mathrm{GHz})^{-1}$ [8] so approximately 10 times better than the gas-cell based filter and the noise equivalent displacement (NED) that is achieved is 1.3 pm/$\sqrt{Hz}$.

Here, we propose to implement an integrated MZI on silicon nitride (Si_3N_4) process (Fig. 2) to perform the OFI FM-to-AM conversion since silicon nitride has low propagation loss and a lower thermo-optic coefficient ($2.45{\cdot}10^{-5}$RIU/°C) compared to silicon photonics ($1.8{\cdot}10^{-4}$RIU/°C) at 1550 nm [11]. The aim is to demonstrate the possibility to fully integrate this conversion on chip, to ease the tuning of the filter and to improve further the resilience regarding temperature and parasitic mechanical vibrations compared to fiber-based implementation [8]. The implemented path-length imbalance is set to 2 cm that corresponds to a 0.83 $(\mathrm{GHz})^{-1}$ sensitivity.

This paper is organized in two main parts. First, in Section II, an overview of the FM OFI signal and the proposed integrated OFI FM-to-AM conversion are presented. In Section III, the experimental setup and results are shown followed by a conclusion in section IV.

II. Integrated OFI FM-to-AM Demodulation

A. FM OFI overview

As previously mentioned, in the case of the AM channel, the OFI induces fluctuations in the optical output power (OOP) of the LD, denoted $P(t)$, given by [1]:

$$P(t) = P_0 \left[1 + m\cos\left(\Phi_F(t)\right)\right], \quad (1)$$

where P_0 is the emitted optical power under free-running conditions, m is the modulation index and $\Phi_F(t)$ is the laser output phase in the presence of feedback. $\Phi_F(t)$ is related to the laser output phase without feedback $\Phi_0(t) = 4\pi D(t)/\lambda_0$ with $D(t)$ the laser-target distance, by [1], [2]:

$$\Phi_0(t) = \Phi_F(t) + C\sin\left(\Phi_F(t) + \arctan\alpha\right), \quad (2)$$

where α is the linewidth enhancement factor of the laser and C the optical feedback factor. Depending on C, the laser can operate in different regimes. SM sensing is generally performed under weak feedback regime ($C < 1$), moderate feedback regime ($1 < C < 4.6$), or strong feedback regime ($C > 4.6$). However, a moderate feedback regime is usually preferred as the apparently simple saw-tooth shaped SM fringes belonging to such a regime [12] intrinsically provide motion direction indication and require simplified SM fringe detection processing [3]. Regarding FM OFI channel, (2) can also be expressed as follows:

$$\left[\nu_0(t) - \nu_F(t)\right]\tau_{ext} = \frac{C}{2\pi}\sin\left(2\pi\nu_F(t)\tau_{ext} + \arctan\alpha\right), \quad (3)$$

where ν_0 is the unperturbed LD frequency, ν_F is the LD frequency, and τ_{ext} is the external round trip time of flight. From (3), the variation of the LD frequency $\Delta\nu = \nu_F - \nu_0$ is strongly constrained as:

$$|\Delta\nu| \leq \frac{C}{2\pi\tau_{ext}}. \quad (4)$$

The design of the optical filter should consider this maximum span to avoid folding. Note that fringe-locking to the half fringe [8] can extend this range further and thus might allow the design of an even steeper filter.

B. The OFI FM-to-AM conversion

As previously mentioned, the OFI FM-to-AM conversion is performed using a Mach Zehnder interferometer (MZI) shown in Fig. 2. The output power P_{out} can be expressed as:

$$P_{out} = P_{in}\left[1 + \cos\left(2\pi n(\nu)\frac{\Delta d_{path}}{c}\nu\right)\right], \quad (5)$$

where P_{in} is the injected light power in the MZI, Δd_{path} the MZI path difference length, n the refractive index of the optical path and c the speed of light. As mentioned in [8], the maximum sensitivity S is achieved at the middle of the transmission power response of the MZI. It is given as:

$$S = \frac{1}{P_{in}}\frac{\partial P}{\partial\nu} = 2\pi n_g(\lambda)\frac{\Delta d_{path}}{c}, \quad (6)$$

where λ is the LD wavelength and n_g the group index defined as $n_g(\lambda) = n(\lambda) - \lambda\frac{\partial n(\lambda)}{\partial\lambda}$. In the case of integrated MZIs, it might be more convenient to express S as function of the free spectral range FSR(λ) defined as follows:

$$FSR(\lambda) = \frac{\lambda^2}{n_g(\lambda)\Delta d_{path}}. \quad (7)$$

Consequently, (6) becomes:

$$S = 2\pi\frac{\lambda^2}{cFSR}. \quad (8)$$

In the case of open-loop OFI approach, similar to bandwidth definition, it might be useful to define the range $\delta\lambda_{dyn}$ for which the sensitivity is reduced by a factor of $\sqrt{2}$. It can be shown from (6) that $\delta\lambda_{dyn}$ can then be approximated by:

$$\delta\lambda_{dyn} \approx \frac{\lambda^2}{4n\Delta d_{path}}. \quad (9)$$

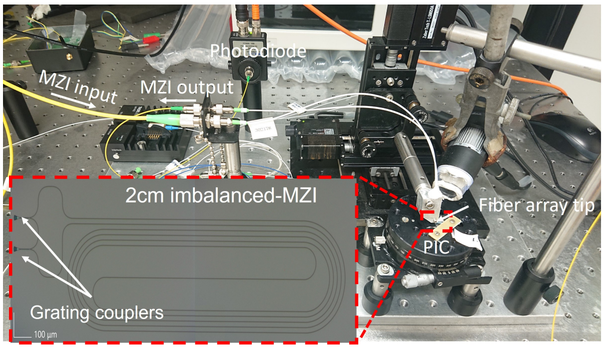

Fig. 3. Experimental setup with the fiber array and the integrated photonic chip including the 2 cm imbalanced MZIs shown in the inset (microscope photograph).

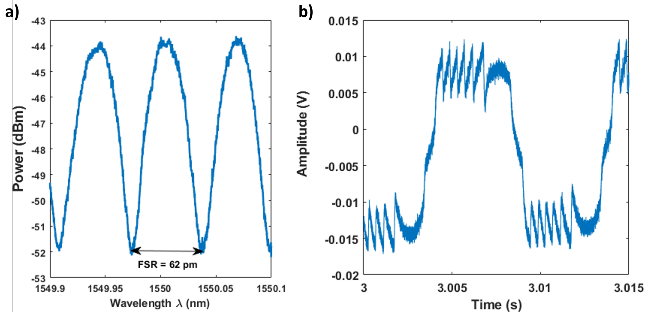

Fig. 4. a) Optical transmission spectrum of the 2 cm imbalanced MZI b)OFI output signal obtained after OFI FM-to-AM conversion using a) MZI for a speaker (target) vibrating at 100 Hz.

This conversion range should ideally cover not only the LD wavelength variation induced by OFI but also the wavelength variation induced by current modulation that might be required for dithering [13]. There is thus a trade-off between sensitivity and conversion range for open-loop configurations.

III. Experimental Results

A. Experimental set-up

The experimental set-up described in Fig. 2 is shown in Fig. 3. The light source is a pigtailed laser diode WSLD-1550-020m from Wavespectrum emitting 8 mW of power at λ=1550 nm. This emitted light is then injected into two branches using a fiber coupler with a splitting ratio of 80/20 as shown in Fig. 2: (1) the measurement branch which connects the laser to the target and (2) the OFI FM-to-AM conversion photonic chip. Here, a speaker is used as a target. The OFI FM-to-AM converted output of the photonic chip is monitored by the photodiode PDA50B-EC from Thorlabs.

The laser-target distance is currently approximately 2.5 m, which corresponds to $\tau_{ext} \approx 24$ ns. Based on (6), the maximum variation $\Delta\nu$ that can be observed in moderate feedback regime is approximately 30 MHz.

The integrated photonic circuit is fabricated using a 300 nm Si_3N_4 process with a refractive index $n_{Si_3N_4} \approx 2$ (Fig. 2). An MZI, with an imbalanced path length of 2 cm (inset of Fig. 3) was designed and inmplemented. This 2 cm MZI has been characterized and reported using the set-up shown in Fig. 1.The light from the fiber is injected into the integrated photonic circuit via integrated grating couplers using a fiber array with a 8° polishing angle.

B. MZI characterization

Fig. 4 a) shows the optical transmission spectrum of the 2 cm imbalanced MZI using an APEX206 optical spectrum analyzer. As expected, the FSR is approximately 62 pm, which corresponds to a sensitivity of $\approx$0.83 (GHz)$^{-1}$. Note that the displayed MZI spectrum takes also into account the injection loss into the integrated photonic circuit via the grating couplers ($\approx$ 11 dB/coupler) and also the propagation loss ($\approx$ 1 dB/cm) in the Si_3N_4 waveguide.

C. OFI FM-to-AM noise performances

Fig. 4 b) shows a typical OFI signal obtained after OFI FM-to-AM conversion using the integrated MZI. The photodiode was set with a gain of 20 dB. The NED can also be estimated as expressed in [8]:

$$NED = \frac{\lambda}{2}\frac{V_{RMS}}{V_{pp}}, \tag{10}$$

where V_{pp} is the peak-to-peak amplitude of the OFI signal and V_{RMS} the OFI RMS noise. Here, the currently achieved NED is approximately 16 nm for 1 kHz bandwidth.

IV. Conclusion and Discussion

We have demonstrated the possibility to fully integrate an OFI FM-to-AM conversion for OFI applications. The sensitivity is 0.83 (GHz)$^{-1}$ for a 2 cm imbalanced MZI. The NED is approximately 16 nm, which is approximately more than two orders of magnitude larger than [8]. Nevertheless, the sensitivity could be enhanced in future design with longer imbalanced MZI and shorter laser-target distance for instance. In addition, noise performances can also greatly benefit from better injection performance by using edge couplers [14] instead of grating couplers and reducing the waveguide propagation loss down to a few dB/m as in [15].

The advantages of the integrated OFI FM-to-AM conversion are its compactness, its ability to be electrically tuned and also to be thermo-regulated more easily than fiber based approaches. To achieve higher sensitivity, other type of filters based on integrated photonic filters can also be envisioned. This integrated OFI FM-to-AM conversion paves the way to more compact OFI FM-to-AM converters compared to fiber-based approaches.

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