Athermal Silicon Photonic Wavemeter with Wide Temperature Range

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Abstract: We demonstrate a silicon photonic wavemeter with high accuracy for broadband measurements over a large temperature range of 20-60˚C. The integrated wavemeter reaches a mean error of 11 pm over an 80 nm span.

1. Introduction

Wavemeters enable calibration, stabilization, and tracking of lasers for important applications including optical communications, spectroscopy, and metrology. While wavemeters based on interferometers with moving mirrors or etalons, or camera sensors measuring speckle patterns have been used, integrated wavemeters promise reduced costs, smaller instrument size, and elimination of moving parts. Several recent demonstrations of integrated wavemeters have highlighted this potential. Using integrated photonics, wavemeters based on arrayed waveguide gratings, modulated waveguides, or Mach-Zehnder interferometers (MZIs) have been shown [1–4]. Attempts have also been made to reduce the temperature dependence of integrated waveguides, by using materials with lower thermo-optic coefficients (TOCs) or TM polarization, but temperature control is still needed [5,6].

We demonstrate a silicon photonic wavemeter capable of accurate and broadband measurements over a wide temperature range. The wavemeter is based on MZIs and is passively athermal, allowing wavelength measurement without controlling the temperature. Achieving both high accuracy and a broad operation range on a robust, integrated platform is attractive for applications from optical communications to sensing.

2. Wavemeter design

Our wavemeter principally consists of four Mach-Zehnder interferometers (MZIs) to measure the input signal's wavelength (Figure 1). The MZIs have varying path length differences (ΔL) corresponding to varying free-spectral ranges (FSRs). The combination of large and small FSRs allows simultaneously a large measurement span and high-accuracy wavelength measurement, as explained further below. Additionally, the wavemeter is designed to be passively athermal, i.e., robust in the presence of temperature fluctuations, because waveguides consisting of different materials are used. While three of the MZIs are based on silicon waveguides, the fourth uses silicon nitride, which has a much lower thermo-optic coefficient (TOC). Together, the different TOCs allow cancelling out temperature shifts in the wavelength calculation.

We recently showed how such an athermal wavemeter may measure a laser's wavelength independent of temperature by using MZIs composed of different materials [7]. Here, we will demonstrate operation over a wide temperature range of 20-60˚C. Because large enough temperature shifts in components with periodic spectra result in ambiguity as the spectra repeat, we now also include an integrated temperature sensor (Fig. 1a) to provide an estimate of the device temperature and thereby remove the ambiguity over a wider temperature range. The sensor is a silicon *pn* diode which has a constant current of 1 mA applied during the experiments, while measuring the voltage. Through calibration, a linear fit of voltage versus temperature is obtained and can be used for estimating the temperature during wavemeter operation.

The procedure for calculating the wavelength involves applying MZI measurements to subsequent MZI stages of increasing ΔL (Figure 2). First, the wavelength obtained from the phase measurement of MZI-0 is used to determine the relevant order m of MZI-1. Then, the wavelength obtained from the phase measurement of MZI-1 is used to determine the relevant orders m of MZI-2 and MZI-3. The wavelength (or optical frequency ν) measurement is obtained by first measuring the MZI phases. The phase difference of MZI-2 φ_2 measured by the detectors, for example, is related to ν, dispersion b, TOC θ, and temperature ΔT (relative to the lowest temperature) by:

$$\varphi_2 = \Delta L_2 \frac{2\pi\nu}{c}\left(n_{g2} + \theta_2 \Delta T\right) + 2\pi b_2 \Delta L_2. \quad (1)$$

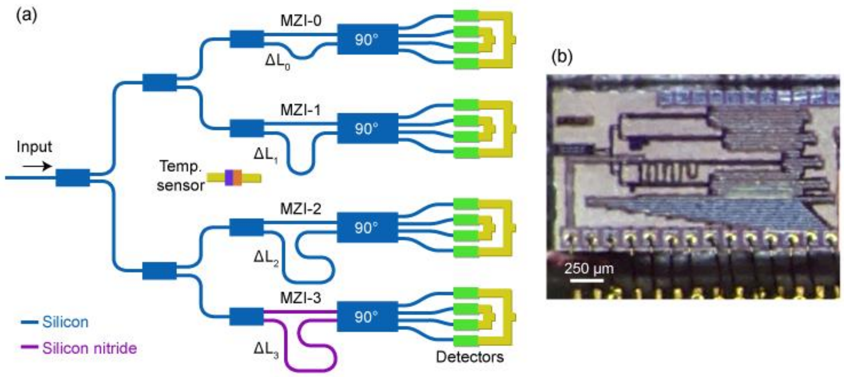

Fig 1. (a) Diagram of the athermal wavemeter, including four MZIs composed of silicon or silicon nitride. (b) Microscope image of fabricated silicon photonic wavemeter, with wirebonds on the bottom edge.

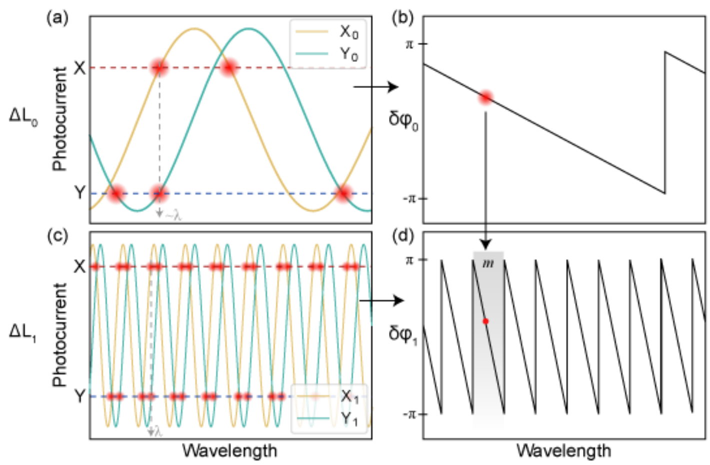

Fig 2. (a) Exemplary spectrum of an MZI with a small ΔL_0 and large FSR. The red dots indicate the wavelength approximated by the photodetector current measurements X_0 and Y_0. (b) Relative phase inferred from the large-FSR MZI's photocurrents. (c) Spectrum of an MZI with a large ΔL_1 and small FSR. (d) Relative phase inferred from the small-FSR MZI's photocurrents and from the order *m* as determined by the phase of the large-FSR MZI.

It can be shown that ν is unambiguously known from the measurements of φ_2 and φ_3 even when the temperature is unknown:

$$\nu = \frac{c}{2\pi\Delta L_2\Delta L_3}\frac{\theta_2\Delta L_2\varphi_3 - \theta_3\Delta L_3\varphi_2 - 2\pi\Delta L_2\Delta L_3(b_3\theta_2 - b_2\theta_3)}{\theta_2 n_{g3} - \theta_3 n_{g2}} = \nu_0 + \frac{C_{21}(\Delta\varphi_3 - C_{30}) - C_{31}(\Delta\varphi_2 - C_{20})}{C_{21}C_{32} - C_{31}C_{22}}, \tag{2}$$

where $\Delta\varphi_{2,3} = \delta\varphi_{2,3} + 2\pi\Delta m_{2,3}$ are the unwrapped phases. All of the variables in the center term of the equation are easily determined by one-time calibration and linear fitting to obtain the coefficients C_{ij} [7]. The diode sensor's temperature estimation is used in calculating a relative frequency $\delta\nu$, referring to an offset within a single FSR:

$$\delta\nu_i = \frac{\delta\varphi_i - C_{i0} - C_{i1}\Delta T}{C_{i2} + C_{i1}\Delta T/\nu_0}. \tag{3}$$

This value is then used when the early MZI stages are used to calculate the orders Δm of the subsequent stages:

$$\Delta m_{i+1} = \mathrm{round}\left(\frac{\Delta\nu_i - \delta\nu_{i+1}}{\mathrm{FSR}_{i+1}}\right), \tag{4}$$

where $\Delta\nu_i = \delta\nu_i + \Delta m_i \mathrm{FSR}_i$. This calculation benefits from the initial temperature estimate and ensures that the correct order *m* is used (or else the calculation could deviate by a full FSR). With the order *m* known, the term $\Delta\varphi$ in Eq. (2) may be found, and thereby we obtain the laser's optical frequency ν (or wavelength).

3. Results

The wavemeter is fabricated using a standard 220 nm silicon photonics foundry. The 1×2 mm chip is assembled with an optical fiber and wirebonded to a fan-out board (Fig. 1b). A thermoelectric cooler (TEC) is used to control the temperature of wavemeter chip during testing. We first calibrate the wavemeter using a reference tunable laser to determine the C_{ij} coefficients (as described in [7]). Next, we characterize the accuracy of the wavemeter over a broad wavelength span. We scan the reference laser from 1500 to 1580 nm while measuring the photodiode outputs and calculating the wavelength using Eqs. 2-4 as well as a look-up table of reproducible errors across the spectrum. At 22.5˚C, for example, we compare the measured wavelength across the range to the known wavelength of the reference laser (Fig. 3a-b), finding a mean accuracy of 10.8 pm (1.3 GHz). We next mount a separate wavemeter chip on a TEC and thermally heated base to vary the temperature over a larger range. The measurement error in the C-band is recorded for temperatures from 20˚C to 60˚C. Figure 3c shows that the mean accuracy across the range averages 17.3 pm. The measurements remain accurate across the entire range because the silicon/silicon nitride design automatically removes most temperature dependence. Note that the sensor need not be precise; the *pn* diode sensor used here has an error of 0.5˚C.

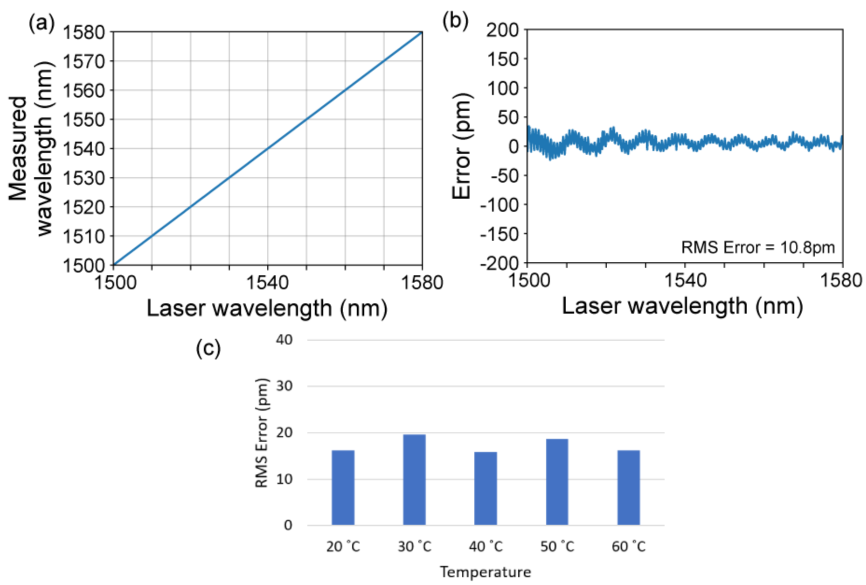

Fig 3. (a) Wavelength measurement from the wavemeter at 22.5˚C compared to actual wavelength of the reference laser. (b) Deviation of the wavemeter measurement from the known laser wavelength. (c) Mean measurement errors of the wavemeter over the C-band spanning 20˚C to 60˚C.

4. Conclusion

We have shown the first athermal wavemeter using silicon photonics demonstrated over a wide temperature range. Based on MZIs composed of waveguides with different materials and TOCs, the wavemeter can unambiguously determine the wavelength of an input laser over an 80 nm range. We show mean error as low as 11 pm, and from 20˚C to 60˚C the error in C-band is ~17 pm. Because the remaining error is mostly periodic rather than random (Fig. 3b), we expect further improvements are possible with optimized components or improved calibration.

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6. References

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