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Integrated chip-scale Si_3N_4 wavemeter with narrow free spectral range and high stability

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We designed, fabricated, and characterized an integrated chip-scale wavemeter based on an unbalanced Mach–Zehnder interferometer with 300 MHz free spectral range. The wavemeter is realized in the Si_3N_4 platform, allowing for low loss with ~62 cm of on-chip delay. We also integrated an optical hybrid to provide phase information. The main benefit of a fully integrated wavemeter, beside its small dimensions, is increased robustness to vibrations and temperature variations and much improved stability over fiber-based solutions.

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Wavemeters based on fixed-delay interferometers are commonly used to estimate wavelength sweep rates and linearize continuously tunable laser sweeps [1,2]. Various types of interferometers can be used for this application, and commonly Mach–Zehnder or Michelson interferometers are employed. Such interferometers are typically realized in fiber. The benefit of using a fiber lies in extremely low propagation loss, allowing for practically arbitrary path length imbalance and consequently arbitrary free spectral range (FSR) of the interferometer. However, polarization stability of fiber-based interferometers can be a problem. One way to compensate for polarization fluctuations is the use of polarization-maintaining fiber and components, but this comes at the expense of significantly higher cost. Another approach, suitable for Michelson-based architecture, lies in the use of a Faraday rotating mirror [3]. An ideal Faraday rotator followed by a mirror cancels any effect of the medium birefringence and guarantees that the beam always returns in orthogonal polarization state with respect to the input state. Nevertheless, fiber-based interferometers still suffer from sensitivity to vibrations and temperature variations and are relatively bulky in size.

Chip-scale integration can improve the stability and provide reduced cost, size, and weight. Moreover, it is essential to adopt a chip-scale solution for an on-chip tunable laser source in terms of wavelength monitoring and possible correction or stabilization. We designed a chip-scale Mach–Zehnder-based interferometer realized in a low-loss Si_3N_4 waveguide platform. The use of a Si_3N_4 waveguide platform brings a few key benefits: low propagation loss and high polarization extinction ratio. Losses as low as 0.045 dB/m have been demonstrated around 1580 nm using 40 nm thin Si_3N_4 films [4]. Here we use a thicker 90 nm Si_3N_4 film as it allows for tighter bends and reducing the wavemeter footprint. The width of the Si_3N_4 waveguide is 2.8 μm. The area occupied by the 62.1 cm long delay line is 3.5 mm × 6.5 mm, and the total chip size comprising two wavemeter designs is approximately 8 mm × 13 mm. We show both designs in Fig. 1. Due to the high aspect ratio together with tight waveguide bends, Si_3N_4 waveguides provide very high polarization extinction, up to 75 dB [5], making the Mach–Zehnder type interferometer extremely stable in terms of polarization.

We designed two types of wavemeters that we call A and B (see Fig. 1). Type A is an unbalanced Mach–Zehnder interferometer (UMZI) that can be used to count fringes and monitor the sweep, but cannot be used to detect the phase as its two

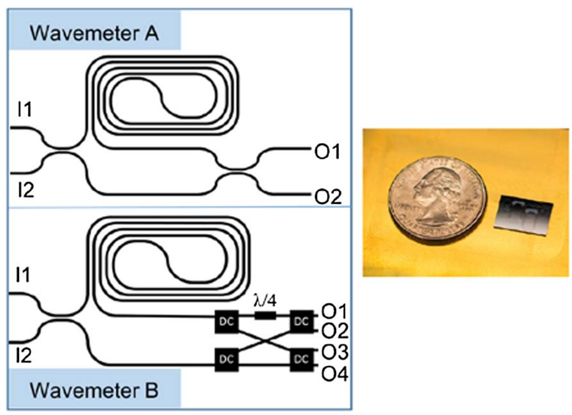

Fig. 1. Design of wavemeter A, an unbalanced Mach–Zehnder interferometer with 62.1 cm of length unbalance, and design of wavemeter B, an unbalanced Mach–Zehnder interferometer with an optical hybrid that allows for phase measurement. The right figure shows the size comparison of the chip comprising two types of wavemeters with a U.S. quarter coin.

outputs are phase inverted (180° phase shift). Detection of phase allows for more precise wavelength tracking as well as detection of the direction of the wavelength sweep, so sweep reversals can thus be accounted for and tolerated. In fiber, this is commonly achieved by using 3 × 3 fiber couplers that produce 120° phase shifts between the outputs [6]. A 3 × 3 multimode interference (MMI) coupler could provide the same functionality [7], but here we adopt a bit different approach. We introduce an optical hybrid in the Type B design to provide in-phase (I) and quadrature (Q) output demodulation of the phase. Optical hybrids are commonly used in coherent receivers for the same functionality. As shown in Fig. 1, the optical hybrid comprises four 50/50 directional couplers and waveguide interconnections in between. Specifically, the uppermost branch includes a $\lambda/4$ optical delay design based on the center wavelength of 1550 nm. Selective combination of the ports can thus have 90° phase shift with each other, thus forming the so-called I (in-phase) and Q (quadrature) channels. By using I and Q, a complex representation of the output signal can be found. The phase of that signal, scaled by FSR, represents the wavelength. Having multiple outputs can also improve wavemeter measurement resolution. As the Type B design is identical with Type A except for the additional optical hybrid and additional functionality, we show our measurement results and analysis of the Type B wavemeter with optical hybrid in the following paragraphs.

The wavemeters were fabricated in-house at the University of California, Santa Barbara. The device was fabricated by depositing stoichiometric silicon nitride (Si_3N_4) on a silicon wafer with 15 μm of thermal oxide. This layer of Si_3N_4 is patterned with 248 nm deep UV lithography and dry etched using an inductively coupled plasma reactive ion etcher with $CHF_3/CF_4/O_2$ plasma. After removal of the photoresist, reactive ion sputtering is used to deposit 1.6 μm of upper cladding to complete the waveguide. We use inverse tapers to improve the fiber coupling efficiency. Coupling loss to cleaved fiber is measured to be <3 dB per interface. The couplers in the UMZI were designed to compensate for higher propagation loss in the longer arm, but some fringes have reduced extinction ratios (ER) due to higher than expected propagation loss. We measured the propagation loss utilizing optical frequency domain reflectometry to be around 0.186 dB/cm. The insertion loss of individual outputs based on swept laser measurement is shown in Figs. 2(a)–2(c). Measurement indicates the usability of the designed wavemeter over a wide wavelength range (1525–1575 nm). Clear fringes are obtained and the FSR is found to be ~2.4 pm (corresponding to 300 MHz). This small FSR is suitable for high-precision wavelength monitoring and correction. Meanwhile, from the wavelength response some phase shift can be seen between the output ports. For example, outputs O2 and O3 can serve as I and Q to be used for the demodulating phase and, consequently, the wavelength of the input signal. The total insertion loss of the wavemeter is less than 15 dB (including coupling and waveguide loss). It's noted that the power levels and extinction ratios vary between output ports. This phenomenon results from the inaccurate estimation of the waveguide propagation loss and inconsistent power splitting ratio of the directional couplers with design targets due to fabrication imperfections. This can be easily fixed by modifying the directional coupler length in future runs. The wavemeter offers up to 18 dB extinction ratio around 1550 nm and both

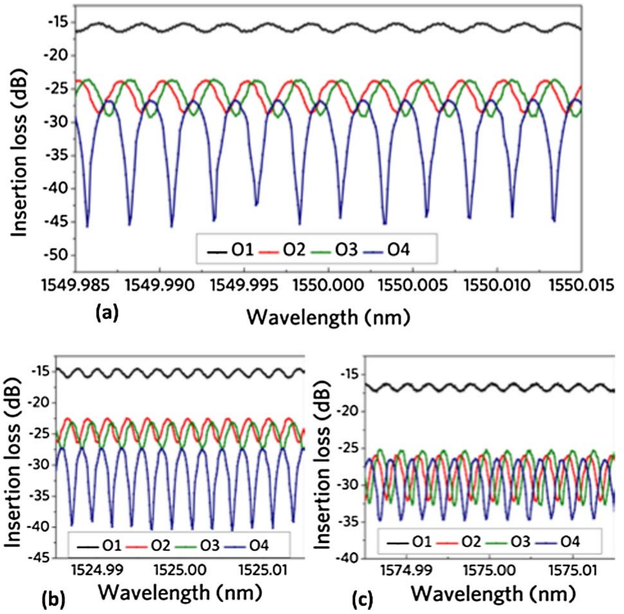

Fig. 2. Measured response of the wavemeter around (a) 1550, (b) 1525, and (c) 1575 nm. The ports are marked on Fig. 1.

the extinction ratio and the phase shift between the outputs are largely insensitive to temperature changes. Thus, the wavelength estimation shows high robustness to temperature variations.

A high extinction ratio together with clear fringes are desired in the frequency response of a wavemeter. Moreover, it is beneficial if the wavemeter can operate over a large temperature range without performance degradation or FSR fluctuation. In our wavemeter design, the adopted Si_3N_4 platform has a low thermo-optic coefficient $(dn/dT = (2.45 \pm 0.09) \times 10^{-5}(\mathrm{RIU}/°\mathrm{C})$ at 1550 nm according to Ref. [8]), which makes it ideal for integrated wavemeter design beside its low loss property and suitability for enabling a large optical delay. It can be seen in Fig. 3 that the port with the highest extinction ratio (O4) maintains a nearly constant ER of ~17.5 dB over 15°C–50°C temperature range.

In addition to the extinction ratio, the phase shift of output ports is also largely insensitive to temperature change (Fig. 4). Figures 4(a)–4(c) show normalized wavelength response of all

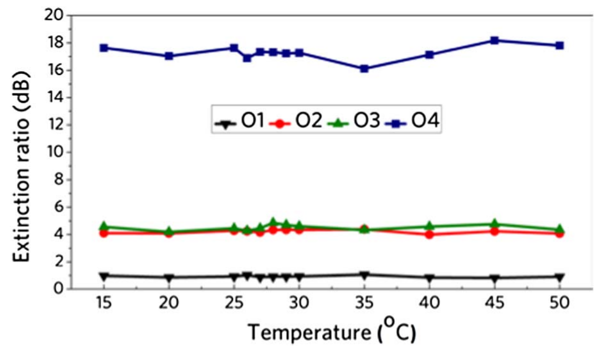

Fig. 3. Extinction ratio versus temperature for different output ports near 1550 nm.

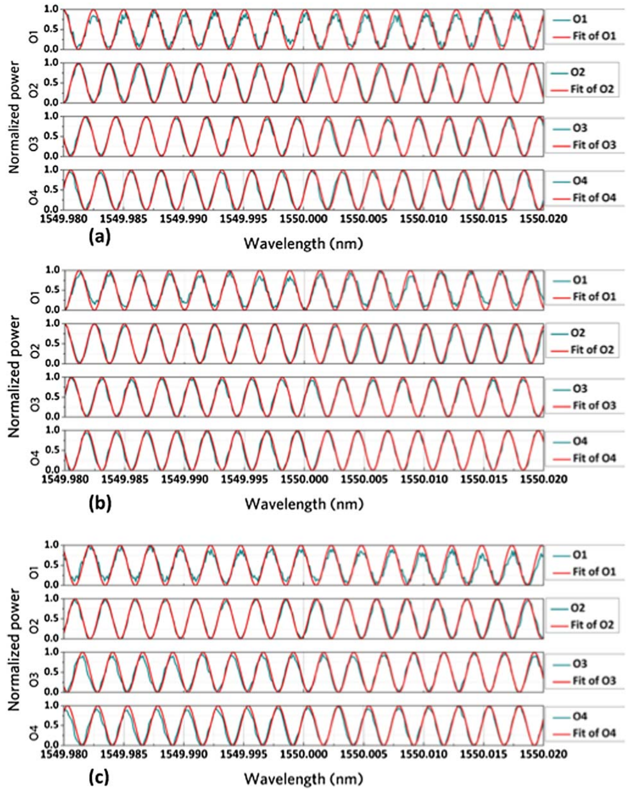

Fig. 4. Normalized output power at different ports at a temperature of (a) 27°C, (b) 15°C, and (c) 50°C. Red curves are sine best fits having 0°, 180°, 90°, and −90° phase difference to that of O1.

four outputs on a linear scale at 27°C, 15°C, and 50°C, respectively. The red curves are the sine function best fits of the corresponding data, with relative phase shifts set to 0°, 180°, 90°, and −90°. The excellent fit of experimental data indicates that the phase response is consistent with the design. Moreover, the fit is repeatable at different temperatures. It could be concluded that although the optical hybrid is dependent on the accuracy of the $\lambda/4$ optical delay, which may be influenced by the temperature, the integrated Si_3N_4 platform enables a largely temperature insensitive operation.

Another benefit of the integrated chip-based optical wavemeter is its increased robustness to vibration and temperature variations and much improved stability over fiber-based solutions. In practice, the operation of fiber-based unbalanced Mach–Zehnder interferometer, which forms the commonly used fiber-based wavemeter, is unstable over time. In order to compare its stability with our wavemeter chip, we conducted the stability comparison test in a setup shown in Fig. 5(a). A Brillouin single-frequency narrow-linewidth fiber laser source output (with high power stability, ±2% over hours) was split into two branches and then fed into the fiber UMZI and our wavemeter chip, respectively. Before the fiber UMZI, an optical variable attenuator (VOA) was used to equal output powers from the fiber UMZI and the chip. Since the fiber UMZI does not have an output optical hybrid, the stability of the interferometers is determined based on the fluctuations of power. As the fibers in the setup are not polarization-maintaining, two polarization controllers are used in both branches as shown in the experimental setup in

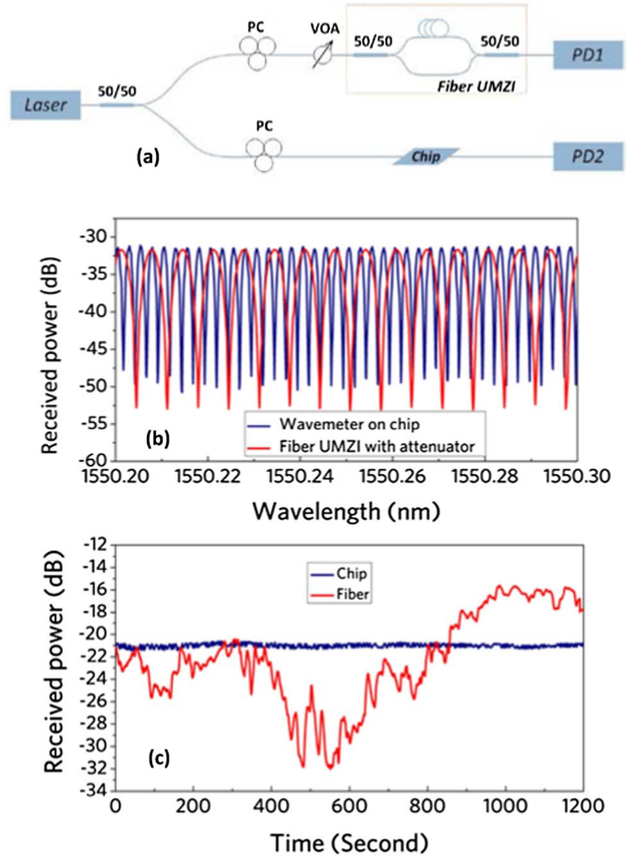

Fig. 5. (a) Experimental setup for the stability test (PC, polarization controller; VOA, variable optical attenuator; PD1 and PD2, photodetector; 50/50, 3 dB fiber coupler), (b) wavelength response (tunable laser output of 0 dBm) and (c) received power in the stability test over 20 min (fiber laser output of 17 dBm), of wavemeter chip and an optical fiber-based unbalanced Mach–Zehnder interferometer.

Fig. 5(a). Before the stability test, we measured the wavelength response of the fiber-UMZI (with attenuator) and chip wavemeter (at port O4) using a tunable laser source with output power of 0 dBm. The result is shown in Fig. 5(b) and we can see that the fiber UMZI has a FSR of around 800 MHz and an extinction ratio of ∼20 dB. The stability test results are shown in Fig. 5(c). The chip wavemeter output power variation is within 0.7 dB, while the fiber UMZI output power fluctuates 16.5 dB. The comparison clearly shows that the fiber UMZI is more vulnerable to the uncontrolled instabilities from the environment and that the integrated wavemeter is much more robust in terms of stability, as expected. It is worth mentioning that this wavemeter is for applications in the telecommunication C band.

To conclude, we have fabricated and characterized a chip-scale wavemeter with a record low free-spectral range of 300 MHz. The key benefits of integration are reduced dimensions and much improved stability. The phase information provided by an optical hybrid is highly desired for a wavemeter. The wavemeter can be integrated with on-chip photodetectors [9] and a laser source [10].

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