# Silicon-based Integrated Broadband Wavelength-meter with Low Temperature Sensitivity

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**Abstract:** We demonstrated an integrated broadband wavelength-meter with three optical 90-degree mixers, differential photodiodes, and delays of thin TM waveguides, allowing unambiguous wavelength determination over 4 THz with high accuracy and relaxed requirement on temperature control. 

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## 1. Introduction

Silicon-based photonics integrated circuits have many unique advantages and have been used in diverse applications including transceivers, lasers, sensors, etc [1]. In some applications, there is a need to detect the wavelength or frequency of an optical signal. This can be done with a filter with frequency dependent optical transmission. Examples include a ring resonator and a Mach-Zehnder interferometer. There are two key specifications: wavelength range and wavelength accuracy. The first one relates the free spectral range (FSR) of the filter, which often inversely affects the accuracy. The second one relates to many factors in the optoelectronic design, among which the most important is temperature. This is because the filter response shifts with temperature due to thermo-optical index change of the material. Unfortunately, silicon has a strong thermo-optical coefficient of 1.84E-4/K near 1550 nm at room temperature, which is 18 times that of silica. As a result, pure silicon has a temperature sensitivity of about 10.2 GHz/C, in comparison with 1.3 GHz/C for silica. Therefore, it is highly desirable to have reduced temperature sensitivity on silicon, while harvesting the benefits of silicon photonics to integrate other functionalities such as photodiodes etc. There are several known techniques to reduce the temperature sensitivity of silicon waveguides. One technique uses cladding materials with negative thermo-optical coefficient over silicon waveguide to cancel out the index change [2]. Unfortunately, such materials are not readily compatible in commercial foundry processes. Another technique uses two different types of waveguides (for example, a wider waveguide and a narrower waveguide) in the filter, both having positive but different thermo-optical coefficients that can cancel out the net temperature dependence with proper balancing of their lengths [3]. However, it becomes difficult if very small FSR is needed.

Here we describe a silicon-based, integrated broadband wavelength-meter with three parallel self-delayed optical 90-degree mixers [4,5] and differential photodiodes, where the delay lines are built with thin TM waveguides. The three parallel mixers have FSR ratio of approximately 10 from one to the next, allowing wavelength determination over 4 THz and with high accuracy simultaneously. The delay lines of thin TM waveguides provides a significantly reduced temperature sensitivity of -2.8 GHz/C, allowing less stringent temperature control of the chip.

## 2. Design

Figure 1(a) shows a schematic of the integrated wavelength-meter. The input light is split to four ways. The bottom branch is directly connected to an integrated photodiode for input power monitoring. The other three branches are each connected to a sub-unit of wavelength-meter based on the 90-degree mixer. Within the unit, light is split into two waveguides with a given relative delay, and then connected to a 2×4 multimode interferometer (MMI), followed by four integrated photodiodes connected differentially to form two signals termed as $S_I$ and $S_Q$. Ideally, the optical frequency can be calculated as $f = \frac{c_0}{n_{eff}(f)\Delta L}(m + \frac{1}{2\pi}\tan^{-1}(S_Q/S_I))$, where $c_0$ is the speed of light, $n_{eff}(f)$ is the effective index of the delay waveguide, $\Delta L$ is the physical length of the delay, and $m$ is an integer because of the periodic nature in FSR. In practice there are imperfections in MMI amplitude and phase responses. Alternatively, one can directly use the values of $S_I$ and $S_Q$ after normalizing to the input power obtained from the separate photodiode. The two signals are sinusoidal curves of frequency, and the 90-degree shift guarantees that at least one of them would always have large slope sensitivity over the FSR. The smallest slope is 4.4 at the crossing point of the two curves. This means frequency change of 1% of FSR leads to 4.4% change in the signal amplitude, which should be reliably measurable. Also, since $S_I$ and $S_Q$ are used separately (instead of their ratio), the impact of amplitude and phase imperfections are less of a concern. To handle the ambiguity associated with the FSR and $m$ over a wide wavelength range, here we use three parallel copies of the wavelength-meter with delay length of $\Delta L_0$, $10\Delta L_0$ and $100\Delta L_0$, respectively. Such a configuration allows unambiguous determination of the frequency with increasing accuracy at the subsequent stages.

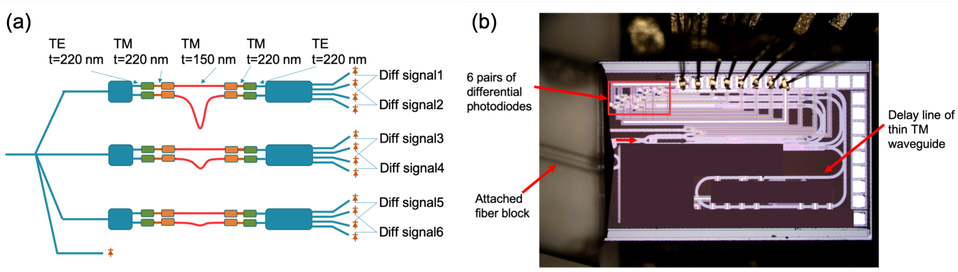


Fig. 1. (a) Schematic and (b) microscope photo of the integrated wavelength-meter chip.

We engineered the waveguide delay to relax the requirement on temperature control accuracy. Because of the large difference in thermo-optical coefficients of silicon and silica, we chose the approach of pushing most of the light out of the silicon core into the silica cladding. This can be done efficiently with thin TM waveguides. Figure 2 compares the TE mode of a silicon waveguide of 500 nm $\times$ 220 nm, and the TM mode of a silicon waveguide of 500 nm $\times$ 150 nm. One can clearly see the drastic difference in mode confinement, and as a result, a 4$\times$ reduction in the equivalent temperature sensitivity of the later to 2.4 GHz/C. In principle such delocalization can also be achieved with the TE mode of very narrow waveguides ($\leq$ 200 nm wide). But those waveguides are typically sensitive to sidewall roughness and suffers strong scattering and back reflection, while the wider and thinner waveguide of TM polarization are much more immune. Since in many cases optical signal is in TE polarization with components built with thicker silicon, as illustrated in Fig. 1(a), we added polarization conversion components to change light between TE and TM polarization, and thickness conversion components to change between 220-nm-thick waveguide and 150-nm-thick waveguide. Also we chose a 1 $\mu$m TM waveguide width to have a tighter bending radius with small degradation in the temperature sensitivity.

Figure 1(b) is a microscope photo of the chip, assembled with wire-bonds to the 12 photodiodes and a fiber block attached at an angle. We note that the wavelength-meter circuit was tapped off another circuit (not shown here) with a tap ratio of around 2%, thus only about 1% of the light from the fiber is transmitted to the wavelength-meter. The weak input and the other circuit affected the characterization of the wavelength-meter. Nonetheless, the principle of operation for the integrated wavelength-meter can be well illustrated.

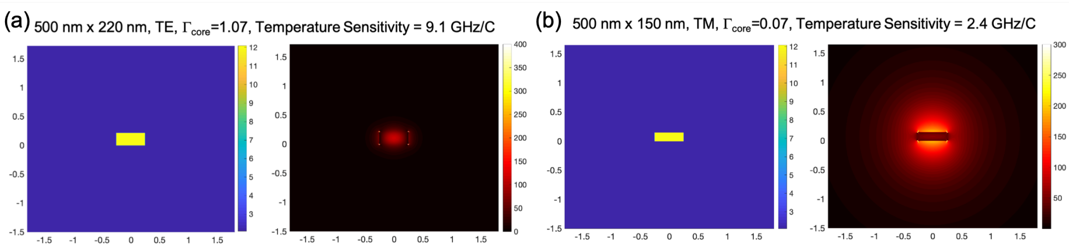


Fig. 2. Comparison of the mode profile and calculated temperature sensitivity between a commonly used TE waveguide and a TM waveguide with reduced thickness.

## 3. Results

We first characterized the responses of the 6 differential signals as a function of input wavelength at room temperature. The results are shown in Fig. 3(a-c), with the two coarser stages covering C-band and the last fine stage covering a 3-nm-wide window. The differential signals ($S_I$ and $S_Q$) in Fig. 3(a) have similar amplitude and roughly 90 degree offset, as expected for the 90 degree mixer. However, imperfections are clearly visible in Fig. 3(b) and (c) in both the amplitude and relative phase. Part of the imperfections comes from the MMI, and a larger portion is caused by the very weak tap ratio and interference from the other circuit in the form of stray light and reflection as noted earlier. For example, photodiodes can pick up slight stray light and shift the response upward, causing errors in the apparent relative phase. Despite this, thanks to the design of parallel stages with $10\times$ ratio in FSR, from the first two stages, one can easily determine the frequency within 10% of their FSRs even with the ripples. The last stage provides the critical accurate frequency reading. Although we did not build the chip into real ADC circuits and perform the full-band calibration, based on the analysis in the design section, we believe a frequency accuracy within +/-0.5 GHz (1.25% of FSR, and 5.5% of signal amplitude accuracy) is obtainable, especially with stronger signal and less noise from other circuits in an improved design.

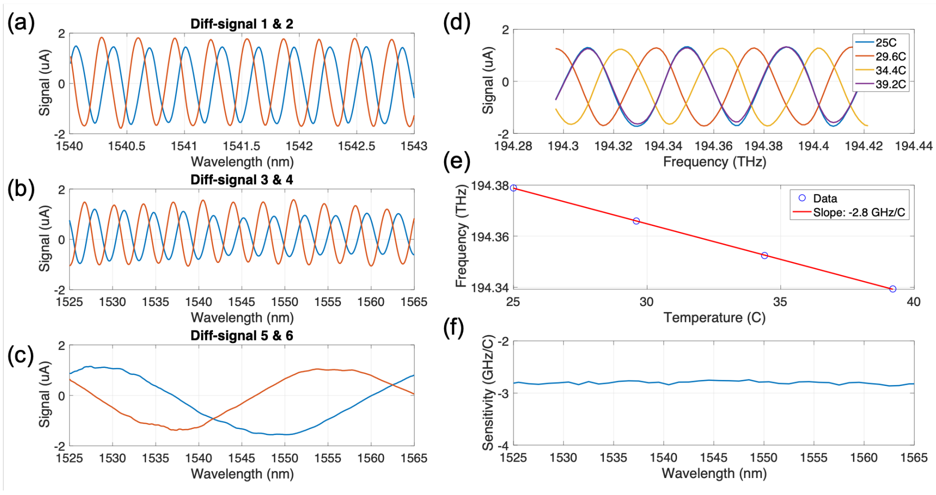


Fig. 3. Measured spectrum and temperature sensitivity: (a-c), spectrum of differential signals over wavelength at room temperature; (d) spectrum of differential signal 1 over frequency at 4 various temperatures; (e) extracted frequency shift over temperature, and temperature sensitivity of -2.8 GHz/C; (f) extracted temperature sensitivity over C-band.

We characterized the temperature sensitivity of the chip to extract the required temperature control accuracy. Figure 3(d) plots the differential signal 1 over frequency at four different chip temperatures. One can see a shift of one full FSR (40 GHz) is observed when chip temperature changes from 25 C to 39.2 C. Figure 3(e) plots the change in a reference frequency point over temperature. The slope, corresponding to the temperature sensitivity, is extracted to be -2.8 GHz/C. Figure 3(f) shows the temperature sensitivity is rather uniform over C-band. If we budget additional +/-0.7 GHz frequency error due to temperature uncertainty, the required temperature accuracy is +/-0.25 C, which is achievable with standard thermistor and thermal-electric cooler (TEC).

## 4. Summary

We demonstrated the design and characterization of a silicon-based, integrated broadband wavelength-meter. The three parallel self-delayed optical 90-degree mixers, and the specially engineered delay lines with thin TM waveguides allow unambiguous determination of signal wavelength over a 4 THz range with high accuracy, and relaxed requirement on the temperature control.

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## References

1. "Silicon Photonics," Proceedings of IEEE, Special Issue, Volume 106, Issue 12 (2018).
2. M. M. Milošević, N. G. Emerson, F. Y. Gardes, X. Chen, A. A. D. T. Adikaari, and G. Z. Mashanovich, "Athermal Waveguides for Optical Communication Wavelengths," Opt. Lett. 36, 4659-4661 (2011).
3. B. Guha, A. Gondarenko, and M. Lipson, "Minimizing Temperature Sensitivity of Silicon Mach-Zehnder Interferometers," Opt. Express 18, 1879-1887 (2010).
4. L. Zimmermann, K. Voigt, G. Winzer, K. Petermann, and C. M. Weinert, "C-Band Optical $90^{\circ}$-Hybrids Based on Silicon-on-Insulator $4\times4$ Waveguide Couplers," IEEE Photon. Technol. Lett., 21, 143 (2009).
5. C. Xiang, M. A. Tran, T. Komljenovic, J. Hulme, M. Davenport, D. Baney, B. Szafraniec, and J. E. Bowers, "Integrated chip-scale Si3N4 wavemeter with narrow free spectral range and high stability," Opt. Lett. 41, 3309-3312 (2016).