

Ultra-high resolution and large range on-chip Fano-enhanced thermometer based on spectral analysis

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Abstract

Temperature detection is essential for evaluating the working condition of various physical, biological, and chemical systems. Optical temperature sensing tools, particularly resonator-based thermometers, have garnered significant attention due to their exceptional performance in selectivity, sensitivity and anti-electromagnetic interference. Recently developed thermometers based on optical whispering-gallery mode barcodes of the microbubble resonator achieve a large temperature range measurement and direct temperature readout. However, the large temperature variation may potentially result in inaccurate results due to similarities in spectra and inadequate precision caused by nonlinear collective shift. In this work, we have developed a novel and directly readable on-chip silicon-based Fano-enhanced thermometer utilizing a Mach-Zehnder interferometer configuration. The device comprises a fishbone waveguide and a curved strip waveguide coupled with an ultra-high Q racetrack microring resonator. The spectrum patterns of the thermometer are uniquely determined by the temperature and exhibit ultra-high slope ratio Fano resonances of over $2.0 \times 10^4 \text{ dB/nm}$. Simultaneously, we have proposed a spectral analysis method to accurately derive actual temperature with a high detection resolution of $6.1 \times 10^{-4} \text{ }^\circ\text{C}$ and a large measurement range of $65 \text{ }^\circ\text{C}$ by leveraging a temperature database. These advancements support precise and extensive temperature sensing applications.

Full Text

Preamble

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Abstract

Temperature detection is essential for evaluating the working conditions of various physical, biological, and chemical systems. Optical temperature sensing tools, particularly resonator-based thermometers, have garnered significant attention due to their exceptional performance in selectivity, sensitivity, and anti-electromagnetic interference. Recently developed thermometers based on optical whispering-gallery mode barcodes of microbubble resonators have achieved large temperature range measurement and direct temperature readout. However, large temperature variations may potentially result in inaccurate measurements due to spectral similarities and inadequate precision caused by nonlinear collective shifts. In this work, we have developed a novel and directly readable on-chip silicon-based Fano-enhanced thermometer utilizing a Mach-Zehnder interferometer configuration. The device comprises a fishbone waveguide and a curved strip waveguide coupled with an ultra-high Q racetrack microring resonator. The spectrum patterns of the thermometer are uniquely determined by temperature and exhibit ultra-high slope ratio Fano resonances exceeding 2.0×10^4 dB/nm. Simultaneously, we have proposed a spectral analysis method to accurately derive actual temperatures, which enables an ultra-high detection resolution of 6.1×10^{-4} °C and a large measurement range of 65 °C by leveraging a temperature database. These advancements support precise and extensive temperature sensing applications.

Keywords: silicon photonics, temperature detection, microring resonator, spectral analysis

Introduction

Temperature is a crucial physical parameter that significantly impacts various physical, chemical, and biological systems. Temperature sensing with high resolution and broad range is of great importance and finds wide applications in diverse fields such as industrial manufacturing [1, 2], environmental monitoring [3-5], and healthcare surveillance [6, 7]. Among sensing techniques, optical sensing technology has gained popularity due to its selectivity, multiplexing capability, and anti-electromagnetic interference.

Recent advancements in thermal sensing have utilized various optical structures, including waveguide Mach-Zehnder interferometers (MZI) [8, 9], photonic fibers [10, 11], and Sagnac interferometers [12, 13]. However, achieving accurate temperature sensing with high resolution based on single-pass (waveguide or fiber) optical sensors poses challenges due to the limited optical sensing path. In a high-quality (Q) factor resonant cavity, light may be recycled millions of times, significantly enhancing the interaction between light and matter and thereby

improving sensitivity [14, 15]. Consequently, optical sensors based on micro-cavities have been developed for temperature detection over the years [16-18].

Among optical resonant cavity sensors, whispering-gallery mode (WGM) resonators have gained popularity due to their high Q factor. The most commonly used sensing mechanism for WGM resonators is tracking single resonance mode shift, due to its easy implementation across a broad range of applications. In addition to sensors based on a single ring resonator, the Vernier effect of cascaded microring resonators (MRRs) has also attracted increasing attention for its ability to effectively enhance temperature sensitivity and sensing range. However, conventional resonant cavity temperature sensors face challenges in direct temperature readout and detecting large temperature ranges. First, temperature detection typically involves monitoring the relative shift of the tracked resonance mode with respect to its original state and calculating temperature based on the thermo-optic coefficient, which varies with temperature and wavelength [19]. Second, large temperature fluctuations may cause the tracked resonance mode to move beyond the laser's scanning range, thereby limiting the sensor detection range.

To address these constraints, a method for direct temperature readout [20, 21] has been proposed by analyzing the collective pattern of the WGM spectrum, which is uniquely determined by temperature. This approach involves calculating collective shifts of the overall spectral patterns using the cross-correlation function [20] or extracting multimode sensing information through a generalized regression neural network [22] that correlates measured spectra with reference spectra in a database to determine the actual temperature. However, large temperature variations may lead to inaccuracies in the collective shifts calculated by the cross-correlation function due to interference from similar spectra. The generalized regression neural network necessitates a vast temperature database with an extremely dense sampling interval of 0.01°C and requires substantial memory and computing resources, thereby limiting the temperature measurement range. Additionally, considering the variation of the material refractive index with temperature and wavelength [23, 24], the same temperature fluctuation in different temperature ranges will lead to nonlinear wavelength shifts, reducing device accuracy.

To address these limitations, we present a Fano-enhanced thermometer (FET) featuring unique and distinct spectrum patterns with thermally sensitive Fano resonance peaks [25-27] at different temperatures. Simultaneously, we propose a spectral analysis method to achieve ultra-high detection resolution and a large measurement range based on the temperature database. The temperature readout process mainly includes two steps: establishing the reference temperature database and classifying correct and incorrect derived temperatures based on spectral analysis. With a sufficiently extensive temperature database range, precise calculations can be made for any temperature within the range, potentially enabling ultra-wide range measurements. As a proof of concept, a temperature database ranging from 15°C to 80°C has been established, and the spectral

analysis method is employed to accurately derive temperature with an ultra-high resolution of 6.1×10^{-4} °C. The device shows promise as a temperature measurement technology for sensor applications due to its superiority in detection resolution and measurement range capabilities.

2.1 Overall Design and Spectra Measurement

The FET is constructed using a silicon-based MZI structure as illustrated in Figure 1a [Figure 1: see original paper]. One arm (Arm1) is a bus waveguide of an ultra-high Q racetrack MRR [28-31] and the other arm (Arm2) is a fishbone waveguide (FBW), which is a strip waveguide assisted by sub-wavelength gratings (SWGs) [32, 33]. The racetrack MRR consists of two straight waveguides of 550 μm and two arc waveguides with a radius of 90 μm . These components are connected by two Euler-bend waveguides with a bending radius gradually transitioning from 1.2 mm to 90 μm . This design facilitates efficient transmission of the fundamental mode with minimal loss and prevents excitation of higher-order modes.

The coupling region structure comprises two concentric arc strip waveguides with different widths and radii. The widths of the arc waveguide and bus waveguide are 3.2 μm and 1.2 μm , respectively. The radii of the arc waveguide and bus waveguide are 90.00 μm and 92.42 μm , respectively. This configuration satisfies the phase matching condition and avoids the excitation of higher-order modes. The central angles () of the two concentric arc strip waveguides are $\pi/8$, ensuring that the racetrack MRR operates in the under-coupling state and achieves a narrower full width at half maximum (FWHM) in resonance wavelength. The FBW in Arm2 is a SWG-assisted strip waveguide with a 0.2 μm -wide strip waveguide and a 1.5 μm -wide grating. The strip waveguide with a width of 1.2 μm at both ends is connected by a tapered waveguide with a length of 20 μm .

The actual temperature readout process is depicted in Figure 1b. The raw spectra at uniform temperature intervals are pre-processed into transformed spectra, and then a reference temperature database is established based on the transformed spectra. Subsequently, the collective shifts between the measured spectra at any unknown temperature and the reference spectra in the database are calculated using the cross-correlation function to derive all possible temperatures and corresponding parameters. A detailed explanation of this process will be provided later.

The SWG has a duty cycle of 0.4 and a period (Λ) of 250 nm, as depicted in Figure 2a [Figure 2: see original paper], which is much less than the Bragg wavelength ($\lambda_B = 2n_{\text{eff}}\Lambda$, @1550 nm) and prevents Bragg diffraction. Figure 2b illustrates the different variation curves of the effective refractive index for the FBW and the strip waveguide as the temperature increases from 25°C to 100°C, leading to different wavelength shifts of the MZI interference peaks and Fano resonance peaks with the same temperature variations.

Three-dimensional finite-difference time-domain (3D FDTD) simulation indi-

cates that light confinement occurs in both the horizontal (xy-plane) and vertical (yz-plane) directions, which means the FBW behaves as a conventional waveguide with an equivalent effective index. In addition, the effective refractive index change of the FBW differs from that of the strip waveguide forming the racetrack MRR as temperature varies. For the bending part of the racetrack MRR, the fundamental mode gradually moves from the center of the waveguide to the edge with increased curvature, without any mode mutation. When the fundamental mode passes through a straight waveguide, an Euler-bend waveguide, and an arc waveguide, as illustrated in Figure 2c, this phenomenon indicates that the structure enables a smooth transition of the mode in the racetrack MRR and effectively avoids the excitation of high-order modes. In the coupling region of the racetrack MRR, only fundamental mode coupling occurs between the bus waveguide and the arc waveguide, as shown in the upper part of Figure 2d. By analyzing the mode components, the TE_0 mode is exclusively present in the arc waveguide, with almost no higher-order modes, such as the first-order mode, as illustrated in the lower part of Figure 2d.

The output spectrum of the FET consists of the MZI spectra and the Fano resonance peaks, characterized by an exceptionally narrow FWHM and high sensitivity to refractive index changes. The analytical expression of the output spectrum is derived using the transfer matrix method. Assuming that the input light intensity is 1, the output electric field is as follows: where a_1 and a_2 represent electric field amplitudes in Arm1 and Arm2, respectively. The phase shifts in Arm1 and Arm2 are denoted as ϕ_1 and ϕ_2 , respectively. Here, α , ϕ , and t represent the roundtrip attenuation coefficient, single-pass phase shift, and transmission coefficient of the racetrack MRR, respectively. The expression in the bracket on the right side of Eq. 1 determines the shape of the output spectrum, and the design concept of the device can be explained as follows.

On the one hand, the ultra-high Q racetrack MRR and FBW exhibit distinct refractive index changes in response to temperature variations, resulting in noticeable changes of ϕ and $(\phi_2 - \phi_1)$. Consequently, the wavelength shifts of the MZI interference peaks and the Fano resonance peaks exhibit differential responses to temperature variations, as shown in Figure 3a [Figure 3: see original paper], which leads to notable alterations in the Fano resonance parameters, including SR, extinction ratio (ER), and Q-factors, even with minor variations in temperature. On the other hand, it should be noted that the ultra-high Q racetrack MRR demonstrates a distinctive output spectrum characterized by a sudden phase transition within an extremely narrow linewidth near the resonance wavelength. The change is minimal and can be regarded as a constant, resulting in the generation of Fano resonance peaks with significant differences in slope ratio (SR). Figure 3b shows the SRs of the Fano resonance peaks with different phases of the MZI spectrum.

To illustrate the superiority of the FBW, simulated spectra are carried out on two FET configurations with and without FBW (the FBW is replaced by a strip waveguide with the same width), under temperature fluctuations ranging

from 30°C to 35°C, as shown in Figure 3c. One of the Fano resonance peaks is chosen as a benchmark for evaluating the relative shifts of the spectra of the two configurations. The device without FBW exhibits nearly zero relative shift because the shifts of the MZI resonance peak and Fano resonance peak are 390.5 pm and 391.2 pm, respectively. However, the device incorporating FBW displays a noticeable relative shift. The shifts of the MZI resonance peak and Fano resonance peak are 443.3 pm and 391.1 pm, respectively. The difference in wavelength shift between the MZI interference peaks and Fano resonance peaks ensures distinctive spectrum patterns at different temperatures, thus mitigating the risk of incorrect collective shifts arising from similar spectra under significant temperature variations. Hence, the FBW and Fano resonances ensure unique and distinguishable spectral patterns at different temperatures.

Figure 4a [Figure 4: see original paper] illustrates the measurement apparatus for output spectra. The output light of the tunable scanning laser (TSL) is modulated as a transverse electric wave and coupled into the FET before being received by a high-resolution optical power meter. The micrograph of the FET and the SEM images of the racetrack MRR coupling area and FBW are shown in Figure 4b, 4c, and 4d.

The normalized transmission spectrum of the ultra-high Q racetrack MRR from 1550 nm to 1554 nm is shown in Figure 5a [Figure 5: see original paper]. In the racetrack MRR, only the fundamental mode oscillates, with no high-order mode excitation. Benefiting from the low-loss Euler-bend waveguides and straight waveguides, the waveguide losses are all less than 0.24 dB/cm and the Q factor of each resonance peak significantly exceeds one million, as shown in Figure 5b. This leads to narrow resonance linewidths and an abrupt phase transition of the FET spectrum occurring in a small wavelength range, facilitating the generation of Fano resonance with an ultra-high SR. The upper part of Figure 5c shows one of the ultra-high Q resonant peaks of the racetrack MRR with a FWHM of 0.68 pm and a Q of 2.25×10^6 . When the racetrack MRR operates in the under-coupling state, the spectral phase is converted from (-) to (+) sharply, while the phase of the wave in Arm2 varies slowly, as shown in the lower part of Figure 5c. Then the two light waves from Arm1 and Arm2 interfere with each other, forming an ultra-high SR Fano resonance with an ER of 23.1 dB and SR of 2.3×10^4 dB/nm, as shown in Figure 5d. The blue balls represent the measurement result of the Fano resonance, and the red solid line represents the simulation result, where the attenuation coefficient and transmission coefficient of the racetrack MRR are 0.9959 and 0.9969, respectively, proving that the racetrack MRR operates in an under-coupling state. The different responses of refractive indices of the FBW and racetrack MRR waveguide to temperature variations are validated by the measured output spectra in Figure 4e. The wavelength shifts of the MZI interference peak and Fano resonance peak are 443.1 pm and 407.9 pm when the temperature increases from 30°C to 35°C. In addition, at 30°C, the ER and SR of the Fano resonance peak pointed by the arrow are 23.44 dB and -2.13×10^4 dB/nm, respectively. With a 5°C temperature variation, the ER and SR alter to 22.37 dB and -1.72×10^4 dB/nm, respec-

tively. The variation of parameters significantly affects the spectrum pattern and prevents the emergence of similar spectrum patterns.

2.2 Process of Temperature Readout and Establishment of Reference Database

We take the temperature range from 15°C to 80°C (limited by experimental apparatus) as a proof of concept to elucidate the direct temperature readout process in detail. The output spectra of the FET are measured at equal temperature intervals in the range from 15°C to 80°C to establish a reference temperature database, denoted as T_{database} . The spectra (from 1550 nm to 1554 nm, with a scanning accuracy of 0.1 pm) within the T_{database} are shown in the left part of Figure 6 [Figure 6: see original paper]. Benefiting from the different temperature response of the FBW and racetrack MRR, a high-density reference temperature sampling interval (ΔT) is not necessary. To reduce the number of collected spectra in T_{database} while maintaining the accuracy of derived temperatures, we set ΔT to 5°C.

Prior to performing the cross-correlation function to compute the collective shift between two output spectra, the spectra should be preprocessed to obtain the transformed spectra. This is because fluctuations in the parameters of the Fano resonance peaks may not be readily discernible in the information-rich MZI interferometric spectrum. Consequently, the raw spectra should be smoothed using a Savitzky-Golay filter and then normalized. Subsequently, the normalized spectra are substituted into the $f(\text{Tr})$ function (Eq. 3) to derive the transformed spectra, labeled as D_{database} and depicted in the right part of Figure 6. This function effectively captures the attributes of the Fano resonance peaks while also reflecting the variation of the MZI interference spectrum (see S1 of the supplementary information). The collective shifts of spectra corresponding to neighboring reference temperatures in the D_{database} are determined by utilizing the discrete form of the cross-correlation function (RDD'), shown as Eq. 4. Considering that the higher the similarity of the two spectra in D_{database} , the greater the maximum value of their cross-correlation function, the maximum value of the cross-correlation function is extracted, denoted as m (Eq. 5). The position of m indicates the relative collective shift between the two spectra.

Figure 7a [Figure 7: see original paper] shows the computation of RDD', collective shift, and m for two spectra corresponding to different reference temperatures, T and T' ($T < T'$), where D and D' represent transformed spectra. The average collective shift between two reference spectra corresponding to neighboring temperatures is 4114, equivalent to 411.4 pm, resulting in a temperature sensitivity of 82.3 pm/°C (details can be found in S2 of the supplementary information). The collective shifts of different temperature intervals in the D_{database} are calculated and plotted in Figure 7b, which differs from the linear shift of a Fano peak.

For any spectrum corresponding to an unknown temperature, after calculating

the collective shifts relative to each reference spectrum in the D_{database} , the collective shifts are compared with the collective shifts in the corresponding range in the reference table mentioned above. If one of the collective shifts is less than the shifts in the reference table, the temperature corresponding to the measured spectrum is probably located in the temperature interval specified in the reference table. For a temperature between two reference temperatures (T_a and T_b , $T_a < T_b$), it can be calculated by Eq. 6. However, given that the spectral collective shift does not exhibit a strictly linear relationship with temperature variations, averaging the two values is essential for enhancing precision, as shown in Eq. 7, which gives the derived temperature.

2.3 Extraction of Correct Results

According to Eq. 6 and Eq. 7, the collective shifts corresponding to one spectrum that appear in pairs at the same temperature interval may be correct. However, due to the characteristics of the cross-correlation function and the periodicity of the FET spectra, one transmission spectrum may yield multiple temperatures (an example is provided in S3 of the supplementary information). Therefore, it is crucial to differentiate between correct and incorrect results. Fortunately, the experimental outcomes indicate that the m values corresponding to any collective shift exhibit noticeable differences between correct and incorrect results.

In the temperature range of 15°C to 80°C, with a sampling interval of 5°C, three different temperatures in each sampling interval are randomly selected for measurement. Additionally, to further verify the reliability of the FET, two temperatures are selected before and after the reference temperature range, and their spectra are measured separately. We finally obtain 41 transmission spectra. The collective shifts relative to reference spectra are calculated, resulting in 132 collective shifts that satisfy the requirements mentioned above (appearing in pairs at the same temperature sampling interval), corresponding to 132 parameters, denoted as m'_i , where $i = 1, 2, \dots, 132$. Obviously, two neighboring collective shifts correspond to a single temperature according to Eq. 7 and Eq. 8, so 66 temperatures are derived. Considering the uniqueness of the transmission spectrum at different temperatures, the ratio of the mean value of the two parameters for the same temperature to the corresponding reference parameters is expressed as $(m'_{2k-1} + m'_{2k})/2m$, where $k = 1, 2, \dots, 66$. For convenience, these are recorded as M .

Based on 41 spectra corresponding to unknown temperatures, 66 possible temperatures are derived. Figure 8a [Figure 8: see original paper] shows the scatter plot of the derived temperatures versus actual temperatures, where each actual temperature corresponds to a measured spectrum. The 39 red balls on the 45° line indicate that the derived temperatures are equal to the actual temperatures within the range of the reference temperature database, while the blue balls represent incorrect results. It should be noted that a spectrum corresponding to 14.38°C does not derive a temperature, while the spectrum corresponding to

81.22°C yields an incorrect temperature; both are outside the range of the reference temperature database. Figure 8b shows the value of M corresponding to each derived temperature. Red balls representing correct results are larger than 0.93, while blue balls representing incorrect results are smaller than 0.93, which is denoted as the reference value. According to the statistical results from the experiment shown in Figure 8, we can conclude that the M value of the correct temperature is always larger than the M value of incorrect temperatures for one spectrum that can derive multiple temperatures.

Hence, the method of extracting correct derived temperatures is as follows: First, it can be concluded that the temperature corresponding to a spectrum is outside the range of the reference temperature database if the spectrum is unable to derive a temperature or if the M value corresponding to the derived temperature is less than the reference value. Second, for a spectrum, the derived temperature corresponding to the maximum M value, which is larger than the reference value, is the actual temperature.

Table 2 shows a comparison of our work with other works reported in recent years. The designed on-chip FET not only achieves ultra-high detection resolution but also realizes a large measurement range and accuracy in the case of a large sampling interval between reference temperatures.

3. Conclusion

In summary, we have demonstrated an ultra-high resolution and large range on-chip FET based on machine learning-assisted spectral analysis. The device is formed by an MZI structure consisting of a FBW and a bus waveguide coupled with an ultra-high Q racetrack MRR. Additionally, we have introduced a machine learning-assisted spectral analysis method to analyze the overall pattern of the spectra uniquely determined by temperature. Due to the ultra-high sensitivity of the ultra-high slope ratio Fano resonance peaks to temperature variation, the detection resolution achieves 6.1×10^{-4} °C. Moreover, the establishment of the reference temperature database significantly extends the device's measurement capabilities, thereby enabling measurement across an ultra-wide range. Leveraging the ultra-high detection resolution and large measurement range of external changes in environmental parameters, the FET can serve not only as a temperature sensor but also measure magnetic field or electric field intensity, gas or solution concentration. Furthermore, the MZI structure design, consisting of a FBW and a curved strip waveguide coupled with an ultra-high Q racetrack MRR, can be adapted to various material platforms, such as Si_3N_4 , LNOI, SiC, etc., to meet diverse and stringent measurement requirements in complex environments.

4. Methods

Device Fabrication: Details about the fabrication processes of the FET can be found in our previous work. The devices are fabricated on a commercial

SOI wafer with a 220 nm-thick top silicon layer and a 2 μm -thick buried oxide layer. A standard ARP6200.13 photoresist layer is spun and then patterned using electron beam lithography. After being carefully developed, the reflowing photoresist process is carried out on a hotplate at 130°C for 60 s. Then, the patterns are transferred to the silicon layer using an inductively coupled plasma etcher. Finally, the remaining photoresist is removed by dipping into 1-methyl-2-pyrrolidinone stripper. Among the fabrication processes of the FET based on multi-mode waveguide, the reflowing photoresist process is a critical step to achieve ultra-low loss waveguides, which can form a smoother etch mask pattern and reduce roughness from plasma dry etching. The reflowing time should also be carefully controlled.

Device Characterization: Device photographs are taken with an Olympus BX51 microscope, in which the excitation light and emission light pass through a set of fluorescence filters. The photoluminescence emission is collected by a CMOS camera. The SEM images of stripe waveguides and the FBW are taken with a Nova NanoSEM 450 FP2053/45 under conditions of 15 kV & 5 nA (TLD-SE) low vacuum imaging, which utilizes a focused electron beam with an extremely short wavelength to scan the sample surface.

Spectra Measurement: The temperature of the test environment is controlled at a certain temperature by the temperature control device (LL-TEC-C02) and maintained for 30 s before collecting the output spectra to ensure test result accuracy. Light from a tunable scanning laser (Santec TSL-510) enters the polarization controller through an isolator and attenuator. To avoid the emergence of optical bistability effects in the ultra-high Q racetrack MRR, the input optical power is decreased to -9 dBm using an attenuator. The low-power TE mode light modulated by the PC is coupled into the designed FET. The output spectra are recorded by a multi-port optical power meter (Santec MPM-210) with a test range from -10 dBm to -80 dBm.

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Data Availability: Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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