Real-time spectral characterization of photonic microchips with femtometer resolution

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Here we present a new measurement method for the characterization of photonic integrated circuits (PIC) with ultrahigh resolution, speed, and sensitivity that outperforms the existing PIC characterization methods. It is an optical heterodyne system employing a tunable laser and a fixed-wavelength laser (termed sweeping optical heterodyne method). By varying the wavelength of the tunable laser that is fed into the photonic microchip, the beat frequency is swept from DC to the GHz range. An outstanding advantage of this method is that it does not require a narrow linewidth and/or precise tunable laser or light modulator. Moreover, there is no need for an additional calibration procedure. The performance of this method is compared with the standard measurement method based on a tunable laser and a photodiode, and 100 times faster measurement speed, 30dB higher sensitivity, and 100 times higher spectral resolution are achieved. The wavelength resolution of <30fm is verified by measuring the spectrum of an unbalanced fiber Mach-Zehnder interferometer. Finally, using this method, we characterized high-quality factor microring resonators that are realized in a new hybrid platform. This new measurement approach, which has superior performance parameters compared to existing methods, has the potential to become an essential characterization tool in integrated photonics.

Introduction

Photonic integration is revolutionizing the field of optics in the same way that integrated circuits revolutionized the world of electronics in the 1960s. PICs and in particular, ultra-high quality factor microresonators have been extensively employed in various emerging applications including optical sensing [1], photonic processors [2], ultra-narrow linewidth lasers [3], precision spectroscopy [4], quantum optics [5], optical filters [6] and nonlinear optics [7]. Their precise optical characterization is essential for optimizing their performance in these applications. However, the characterization of these devices is often limited by measurement techniques, i.e. optical spectrum analyzers or tunable diodes, which lack the sensitivity, speed, and resolution. On the other hand, narrow linewidth tunable lasers suffer from frequency stability during measurement time and, in some cases, need dithering to stabilize [8,9]. In addition to their high cost, their frequency is subject to some degree of uncertainty during a sweep. To overcome these problems, different approaches have been developed [10,11]. However, in most of these studies, experimental findings were validated using other methods, particularly cavity ring-down techniques.

Addressing these limitations, we introduce a novel PIC characterization method termed the "Sweeping Optical Frequency Mixing Method" —SOHO [12]. Leveraging the principles of optical frequency mixing, SOHO incorporates a tunable laser and custom control software to offer a distinctive measurement method. Using this approach, we measured the spectrum of a ~52.5m-long unbalanced MZI and demonstrated 30 fm of spectral resolution over 12 GHz bandwidth, with the added benefit of real-time operation.

Finally, through the characterization of ultrahigh-quality factor ($Q=3\times10^6$) optical resonator, we verified the superior performance of SOHO both in resolution and sensitivity compared to conventional method based on a tunable laser and a photodiode. This new method not only holds great promise for PIC characterization but also for high-resolution spectral measurements of weak optical signals, including applications such as spectroscopy (e.g. Raman and Brillouin), biomedical imaging, and optical sensing.

Working principle and measurement setup

For the resonators with ultrahigh-quality factor ($Q \geq 10^6$), a simple laser scan could result in large measurement errors due to the uncertainties in the laser frequency during the scan [10]. To address this issue, we have implemented an advanced measurement scheme based on the optical frequency mixing process. As depicted in Figure 1, this method involves mixing the output of the sample laser with a reference laser inside a detector. The resulting difference in optical frequencies appears as a distinct peak in the electric spectrum analyzer (ESA). This enables us to map the optical frequency of the sample laser relative to the reference laser into the radio frequency (RF) spectral domain, which can be accurately measured using electronics. As far as the frequency of the reference laser is known, the frequency of the sample laser can be inferred from the ESA output. For the reference laser, we chose a non-scanning laser, i.e. fixed-wavelength laser, since it can remain stable and predictable during measurements compared to a scanning one. The frequency of the scanning laser is compared with the frequency of the reference laser in the ESA, eliminating the need to determine the exact frequency of the scanning laser. Moreover, the frequency deviations and noise of the scanning laser can be automatically detected on the RF spectrum.

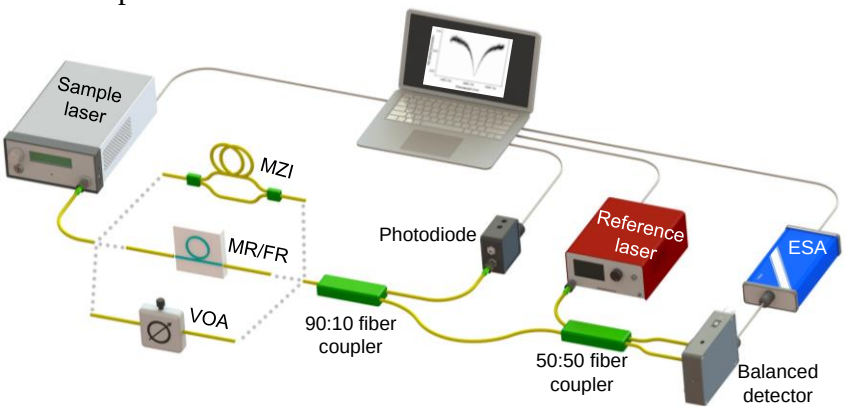

Fig. 1. Schematic of the experimental setup of SOHO. The signal from the variable optical attenuator (VOA) is used as signal reference.

Optical frequency mixing involves two optical signals, whereas the mixing product is an electrical signal. If the device under test is put after the sample laser, by sweeping the frequency of the sample laser, its optical transmittance spectrum, $T(\nu)$, can be extracted from the measured RF spectrum, $P_{log}(f)$. In this configuration the optical intensity after the interference of two lasers is:

$$I(\nu) \propto I_R + I_S + 2\sqrt{I_R I_S T(\nu)} \quad (1)$$

where, I_R and I_S are the intensity of reference and sample lasers, respectively, and $T(\nu)$ is the transmittance of the sample as a function of optical frequency, ν. The detected signal on the photodiode using ESA is proportional to the AC part of the intensity. The ESA measures electrical power spectral density as a function of f and demonstrates it in the dBm scale. By doing some mathematics, $T(\nu)$ is obtained as:

$$T(v) = \frac{Z}{10^3 \alpha^2 I_R I_S} 10^{\frac{P_{\log}(f)}{10}} \quad (2)$$

where, f is the electrical frequency derived from beating of the lasers, i.e. $f = \nu_s - \nu_r$, Z is the input impedance of the ESA, and α is optical to electrical conversion coefficient. The experimental setup of SOHO is shown in Fig. 1. The tunable laser is coupled to the photonic microchip via an optical fiber. The light coming out of the microchip is sent through a splitter and 90% of the light is sent to an amplified photodiode. This part of the setup is the commonly-used tunable laser-based, termed "standard method", and we embedded it into the SOHO setup to be able to make a direct comparison between the two methods. The remaining light is combined with the reference laser through a 50/50 coupler and is sent into a high-speed balanced detector. When the frequency difference of the sample and the reference lasers are within the bandwidth of the photodetector, a beat frequency, f, is detected on the balanced photodetector and measured with the ESA. The output signal has an intensity proportional to the product of the amplitudes of the sample and the reference lasers. Control of lasers, reading the ESA output, and data processing are done using a custom code written in C#.

Spectral measurements using SOHO

A comparison of the spectral measurement results of our fabricated racetrack [13] microresonator (MR) with the standard method and SOHO is given in Fig. 2a. The FWHM of the resonance peak centered at 1550 nm was measured as 9.5 pm, corresponds to an intrinsic quality factor of Q_{int} = 2.7×10^5. To measure the transmission spectrum of the racetrack resonator using the SOHO setup, the reference laser is tuned to a frequency that is 4 GHz lower than the racetrack resonance frequency. The optical frequency of the sample laser is swept between that of the reference laser and 6 GHz away from it in order to measure transmission spectrum of the sample. SOHO has also been performed in real time with 4.15frames/s which is limited by the capture rate of the ESA. Furthermore, compared to the standard method, SOHO provides more than 30dB higher signal.

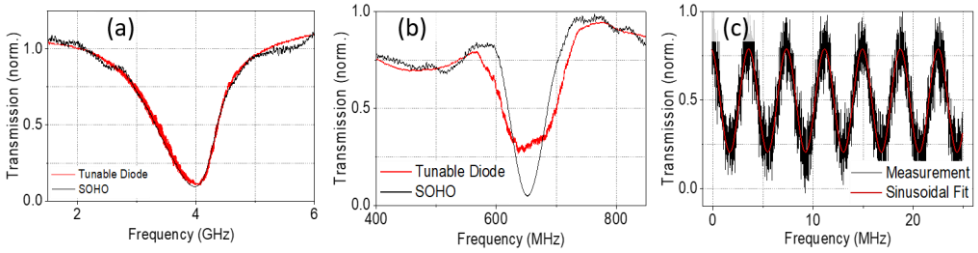

Fig. 2. Transmission spectrum of (a) the racetrack microresonator, and (b) the ring resonator using SOHO (black) and the standard method (red), and (c) a fiber-based unbalanced MZI.

In order to characterize the SOHO setup, we fabricated a fiber ring resonator (FR) and an unbalanced MZI structure with a fiber length difference of ~52.5m, corresponding to an FSR of 3.8 MHz in frequency or 30 fm in wavelength. The spectrum of the fiber ring resonator with a resonance FWHM of around 80 MHz (Q = 3×10^6), a little less than the laser's long-term linewidth, was measured by the standard method and SOHO (Fig. 2b). Since SOHO provides higher resolution and dynamic range, it shows a sharper and deeper resonance dip while it washes out with the low resolution of the standard method, hence our new method is proven to be a more accurate spectral measurement method compared to the standard method.

The spectral measurements of the MZI device were performed by using the SOHO setup as given in Fig. 2c. While the short-term linewidth of the sample laser is less than 100 kHz, it has a frequency dither and as a result, its long-term (millisecond) linewidth is widened to 100 MHz. As a result, the standard method failed to resolve the 3.8 MHz FSR, while our method clearly resolved it.

Conclusions

In this work, we demonstrated a new high-performance PIC characterization method —SOHO that outperforms the current methods in terms of spectral resolution, speed, and sensitivity. Moreover, its setup is formed using cost-effective components and it does not require any calibration, in contrast to current methods. The spectral resolution of 30 fm was achieved, which can theoretically be as small as the linewidth of the reference laser (i.e. kHz range). We measured the spectral response of unbalanced MZIs, high-Q fiber-ring resonators, as well as microresonators that were realized using our new hybrid waveguide technology. SOHO offers the advantage of high sensitivity and precision, making it a valuable tool for researchers and engineers working on the development, testing, and optimization of photonic devices and integrated circuits.

Acknowledgements

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