Scalable Bandwidth and High-Precision Spectral Measurement by Frequency Chirped Comb

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Abstract: *A cost-effective scan technique enabling scalable measurement range is presented by injecting a sweep RF signal of 27.5-30 GHz into an electro-optic comb generator. The 10^{th}-order harmonic scans over an extended span (275-300 GHz) where an ultra-narrow ($Q > 10^6$) resonance is well-resolved with sub-MHz resolution.*
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Integrated resonators with high quality (Q-) factors are highly desirable for a wide range of applications such as narrow linewidth lasers [1], broadband communications [2], ultra-selectivity filter and biosensing [3,4]. Accurate characterization of such high-Q components plays a fundamental role and has motivated research in optical spectral analysis techniques with finer precision. Previously, sub-picometer resolution was achieved using a frequency-swept optical single side band (OSSB) as probe [5]. However, the scan range was fundamentally limited to 1-18 GHz due to the bandwidth of RF components, indicating costly broadband RF devices, particularly high-speed photodetector and modulator were needed [6]. Optical frequency combs have recently been proposed to broaden the overall measurement range to over 100 GHz and even beyond 1 THz. The extended range was covered by stitching the multi-shot measurements where the discrete, widely spanning and equally spaced comb lines were employed as carriers [7,8]. Still, for each measurement channel the scan range (approximately 20 GHz) was tied to the RF component bandwidth. The necessity of deploying an OSSB modulator in addition to a comb generator also made the measurement system complex.

In this paper, we present a frequency-swept comb generator to achieve scan range expansion to 275-300 GHz from a sweep of only 27.5-30 GHz. Different from the existing OSSB modulator based scan method, the proposed method can reach wide single-shot scan range and does not require broadband RF frequency scanning. This is enabled by injecting an electrical sweep signal to a comb generator to produce a series of linear frequency chirped optical signals. This brings several advantages. Firstly, multiple scan lines are simultaneously generated in one single step which simplifies the measurement system. Secondly, a higher order comb line scans over an N-folded range with respect to the electrical sweep signal (where N represents the order of harmonic) relieving the requirement for expensive fast RF components. Furthermore, we use a rather affordable low-speed (125-MHz) photodetector. This not only relaxes the bandwidth requirement but also allows one to monitor the measurement in real time.

Figure 1(a) shows the operation principle for the proposed method. The comb is generated by sending a variable RF frequency (f_e) to modulate a CW source at a fixed wavelength (v_0). The generated comb lines, equivalently a finite set of N-th harmonic components, are thus equally spaced by the RF frequency (f_e) with the carrier $(N=0)$ centered at (v_0). When the modulation frequency f_e linearly sweeps, every single one comb line intrinsically serves as a scanning probe. The scan span largely depends on the order of harmonic, as a higher order comb line scans N times as wide as the sweep RF frequency range. A comb line is then selected with an optical tunable filter as shown in Fig. 2(b) to exclude other unwanted components [9]. As the wavelength of scanning probe at any given time is directly in relation to the known, synchronized electrical sweep signal, the carrier is unnecessary to be included in the optical filter passband as well as the following photodetection. This therefore enables the use of slow photodetector [10].

Figure 2(a) shows the experimental setup. The frequency-sweep microwave signal from the RF synthesizer (frequency: f_e) is modulated onto the CW laser (linewidth: 10 kHz. wavelength: v_0) via cascaded intensity modulator (IM) and phase modulator (PM). To optimize the polarization and wavelength alignment along a frequency span of interest, an EDFA, an optical filter and a polarization controller are employed. The optical signal intensity transmitted through the DUT is subsequently down-converted by an 125-MHz photodetector into the form of electrical temporal trace and displayed on an oscilloscope that is synchronized with the

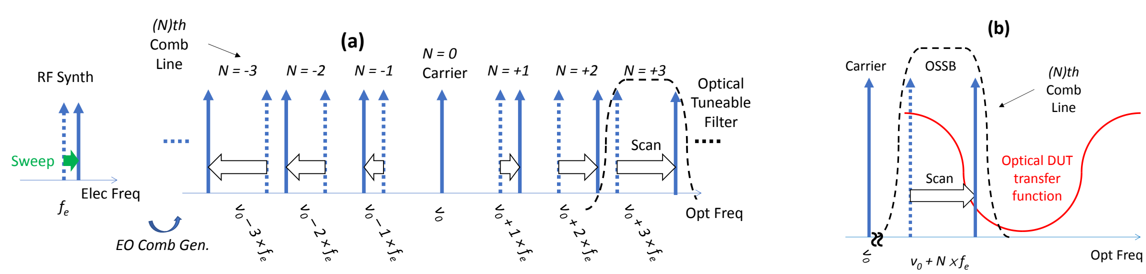

Fig. 1(a) Schematic for the proposed measurement technique. (b) Each comb line is a scan line to probe the DUT. N : the order of comb line. v_0 : the fixed optical carrier (CW laser) frequency. f_e : the swept electrical modulation (RF synthesizer) frequency.

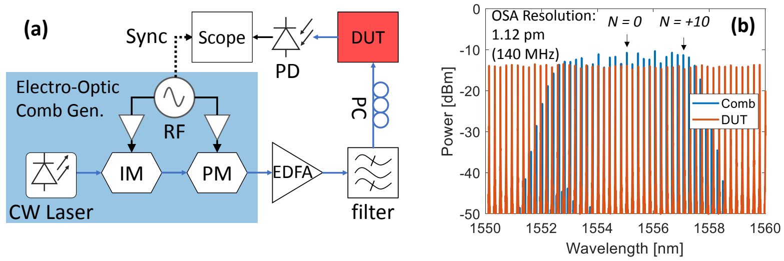

Fig. 2(a) Experimental setup. Blue: Optical links. Black: Electrical links. (b) Spectra of DUT and comb using the 1.12 pm-resolution OSA.

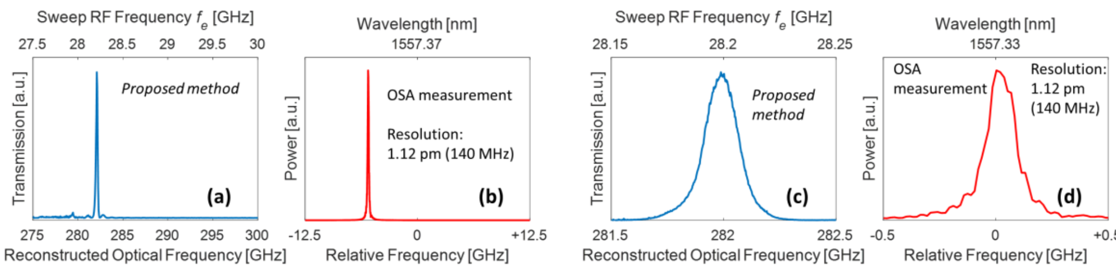

Fig. 3 Measured DUT spectra by (a) proposed approach. Sweep Frequency: 27.5 - 30 GHz. Step: 2.5 MHz, (b) OSA. Span: 25 GHz. Resolution: 140 MHz, (c) proposed approach. Sweep Frequency: 28.15 - 28.25 GHz. Step: 100 kHz, (d) OSA. Span: 1 GHz. Resolution: 140 MHz.

frequency sweeping. Figure 2(b) presents the DUT and comb spectra measured using an optical spectrum analyzer (OSA) with the built-in tunable laser source providing 1.12 pm (140 MHz) resolution. The known DUT exhibits a resonance every 25.5 GHz. When operated with $\nu_0 = 1555$ nm and $f_e = 25$ GHz, the comb spans over 5 nm bandwidth within 6-dB power variation, covering 25 modes equidistant by 25 GHz.

To realize the proposed higher-resolution and range-extended method, a higher order comb line of $N = +10$ was selected with a high-suppression (> 40 dB) optical tunable filter to reduce the residual error caused by the neighboring comb lines of $N = +9$ and +11. A sweep of 27.5-30 GHz with a step of 2.5 MHz was then used, which could be further increased but might degrade spectral flatness of the comb. Figure 3(a) shows the measurement after dark current subtraction and time-to-frequency reconstruction which was interpreted with reference to the optical carrier, i.e., the center ($N = 0$) comb line at $\nu_0 = 1555$ nm. For the resultant frequency span from 275 to 300 GHz a resonance around 282 GHz was spotted, in good agreement with the OSA measurement (Fig. 3(b)) for the same span. Afterwards, to investigate the detail a narrower frequency span (1 GHz, from 281.5 to 282.5 GHz) was adopted as shown in Fig. 3(c), corresponding to the frequency sweeping from 28.15 to 28.25 GHz with a step of 100 kHz. The resonance was clearly seen at 282 GHz with a full width at half maximum (FWHM) of 160 MHz, amounting to an ultra-high quality factor of 1.2 $\times 10^6$. By contrast, the OSA trace revealed the rough profile of the resonance in Fig. 3(d). The OSA resolution bandwidth 140 MHz was close to the estimated FWHM 160 MHz and coarser than the laser linewidth of this proposed approach (10 kHz).

We have demonstrated the comb-scan spectral measurement that offers high resolution and scaled-up range without having to use multi-shot acquisition, fast RF component or dedicated OSSB modulator. This makes it a quick, cheap and simple promising solution alternate to existing ones. Nevertheless, in the proposed method there appears a sweep range limit beyond which the comb flatness and harmonic uniformity will significantly degrade due to phase mismatch. This issue will hopefully be addressed by pre-compensation and self-calibration techniques that we are striving towards.

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