Ultrahigh-resolution coherent optical spectrum analysis based on electrical frequency sweeping with a doubled measurement range

Beibei Zhu, Min Xue and Shilong Pan✉

Based on electrical frequency sweeping, an ultrahigh-resolution coherent optical spectrum analyser with a doubled measurement range is proposed and experimentally demonstrated. In the scheme, a frequency-swept electrical signal is converted to the optical domain. By selecting one of the second-order sidebands of the generated optical signal, a wavelength-swept signal with a frequency range that is twice the bandwidths of the electro-optic and RF components is generated. With the wavelength-swept signal, high-resolution optical spectrum analysis with a doubled measurement range is implemented. In a proof-of-concept experiment, the spectrum of a multi-tone optical signal with a bandwidth of 20 GHz is measured with a resolution of 1.5 MHz by employing 10 GHz components.

Introduction: In emerging applications such as ultrahigh-capacity optical communication [1, 2], on-chip optical signal processing [3] and high-precision optical sensing [4], optical spectrum analysis with high spectral resolution is highly desired. For instance, the frequency spacing of the subcarriers in coherent optical orthogonal frequency division multiplexing (CO-OFDM) systems is as high as tens of MHz [2]. However, restricted by the poor resolution of the conventional gratings-based optical spectrum analyser (OSA) (typically ~2.5 GHz at 1550 nm) [5], the fine structure of the CO-OFDM signal cannot be directly obtained. To achieve the high-resolution optical spectrum analysis, coherent detection methods are developed, which extracts the spectrum of the optical signal under test (SUT) by beating the SUT with a wavelength-swept optical signal. Thanks to the high fineness of the wavelength-swept laser source (WSLS), the resolution is dramatically improved compared to the conventional grating-based OSA [6]. This technique leads to a commercially-available coherent OSA (COSA), APEX AP2040 series with a 0.04 pm (~5 MHz at 1550 nm) resolution [7]. However, restricted by the wavelength accuracy and stability of the WSLS, the resolution is difficult to be further improved. To observe the high-fineness structure of the optical spectra, we have demonstrated an ultrahigh-resolution COSA based on microwave photonics (MWP) [8]. Benefiting from the sub-Hz resolution microwave frequency sweeping, optical spectrum analysis with a resolution of 0.006 pm (about 0.75 MHz at 1550 nm) was realised [8]. One key problem associated with this approach, however, is that the measurement range is restricted by the bandwidth of electro-optic modulators (EOMs) and the frequency-swept RF source.

In this Letter, a novel MWP-based COSA, which has a measurement range that is two times the working frequency of the EOM and the microwave components is proposed and demonstrated. The key component in the proposed approach is an RF-swept optical local oscillator (LO), which has a frequency sweeping range twice the bandwidth of the EOM and the frequency-swept RF source. The RF-swept optical LO is produced by biasing a Mach-Zehnder modulator (MZM) at the maximum transmission point (MATP) which implements optical double-sideband (ODSB) modulation with odd-order sideband suppression, and filtering out one of the second-order sidebands from the generated optical signal. By applying the RF-swept optical LO, the measurement range is doubled.

Principle: Fig. 1 shows the schematic diagram of the proposed MWP-based COSA with a doubled measurement range. An optical carrier from a laser source is modulated by an RF signal at a single-drive MZM biased at the MATP to generate a double-sideband modulated signal with odd-order sidebands suppressed. After filtering out one of the second-order sidebands using an optical bandpass filter (OBPF), a high-resolution RF-swept optical LO is achieved and launched into a 90° optical hybrid. The optical field of the LO can be expressed as [9]

$$E_{\mathrm{LO}} = A_{\mathrm{LO}}\left[\hat{x}\frac{1}{\sqrt{2}} + \hat{y}\frac{1}{\sqrt{2}}\right]\mathrm{e}^{\mathrm{j}[(\omega_0+2\omega_e)t+\theta_{\mathrm{LO}}(t)]} \tag{1}$$

where $\hat{x}$ and $\hat{y}$ are the two orthogonal polarisation axes of the 90° optical hybrid, ω_0 and ω_e are the angular frequencies of the optical carrier and the RF signal, A_{LO} and $\theta_{\mathrm{LO}}(t)$ are the amplitude and phase of the LO signal, respectively. Assuming that the SUT has an arbitrary polarisation state, which is given by

$$E_{\mathrm{SUT}} = A_{\mathrm{SUT}}\left[\hat{x}\sqrt{\alpha}\mathrm{e}^{\mathrm{j}\phi} + \hat{y}\sqrt{1-\alpha}\right]\mathrm{e}^{\mathrm{j}[\omega_{\mathrm{SUT}}t+\theta_{\mathrm{SUT}}(t)]} \tag{2}$$

where α and ϕ are the power ratio and the phase difference of the SUT along the two polarisation axes, A_{SUT} and $\theta_{\mathrm{SUT}}(t)$ are the amplitude and phase of the SUT, respectively. After mixing with the LO in the 90° optical hybrid and detecting each pair of signals in a balanced photodetector (BPD), four photocurrents are produced and recorded by a four-channel analogue-to-digital converter (ADC). After digital signal processing, the spectral component of the SUT at $\omega_0 + 2\omega_{\mathrm{e}}$ is obtained [8], given by

$$|E_{\mathrm{SUT}}| = \frac{1}{|A_{\mathrm{LO}}(\omega_0+2\omega_e)|} \times \sqrt{\frac{2I_{I,X}^2(\omega_0+2\omega_e)}{\Re_1^2} + \frac{2I_{Q,X}^2(\omega_0+2\omega_e)}{\Re_2^2} + \frac{2I_{I,Y}^2(\omega_0+2\omega_e)}{\Re_3^2} + \frac{2I_{Q,Y}^2(\omega_0+2\omega_e)}{\Re_4^2}} \tag{3}$$

where the $\Re_i$ $(i = 1, 2, 3, 4)$ is the responsivity of the BPDs and is a measurable constant, $|A_{\mathrm{LO}}(\omega_0 + 2\omega_e)|$ can be achieved by an optical power calibration process. By sweeping the frequency of the RF source (i.e. ω_e), the spectrum of the SUT with a doubled frequency range is obtained.

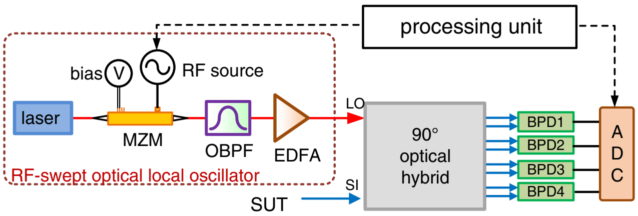

Fig. 1 *Schematic diagram of the proposed MWP-based COSA. RF, radio frequency; MZM, Mach-Zehnder modulator; OBPF, optical bandpass filter; EDFA, erbium-doped fibre amplifier; SUT, signal-under-test; LO, local oscillator port; SI, signal port; BPD, balanced-photodetector; ADC, analogue-to-digital-converter. Red line: polarisation-maintaining fibre, blue line: single-mode fibre, black line: electric cable*

Experimental demonstration: A proof-of-concept experiment based on the setup shown in Fig. 1 is carried out. An optical carrier with a power of 16 dBm is generated from a 3 kHz linewidth laser (Teraxion Inc. PS-NLL-1550), which is then modulated by a frequency-swept RF signal from a microwave source (Agilent E8257D) at a 10 GHz MZM (Lucent Inc.). By filtering out the desired sideband using a tunable OBPF (TOBPF, Yenista XTM-50) and properly amplifying it using an erbium-doped fibre amplifier (EDFA, Amonics Inc.), an RF-swept optical signal is achieved and served as the LO signal. A coherent optical receiver, which is implemented by an optical 90° hybrid (Kylia COH28) and four 100 kHz BPDs (Thorlabs PDB450C-AC), receives the LO as well as the SUT and converts them into photocurrents. A four-channel 10-bit ADC realised by a real-time oscilloscope (Keysight MSOS804A) is employed to digitise the photocurrents. The optical spectrum is achieved by processing the digitised signals. The SUT is an optical multi-tone-modulated signal, which is produced by modulating an electrical multi-tone signal generated by an arbitrary waveform generator (AWG, Keysight M9502A) using another optical carrier at a 40 GHz phase modulator (PM, EOSPACE Inc.). The RF source and the real-time oscilloscope are synchronised by a controlling computer during measurement.

Fig. 2 shows the optical spectra of the ODSB signal and the desired optical signal, which are measured by Yokogawa AQ6370C with a resolution of 20 pm. As can be seen, the odd-order sidebands are well suppressed (blue line). By filtering out one of the second-order sidebands, the RF-swept optical LO is achieved (red line). It should be noted that a calibration step is performed, in which the optical powers at different frequencies are measured.

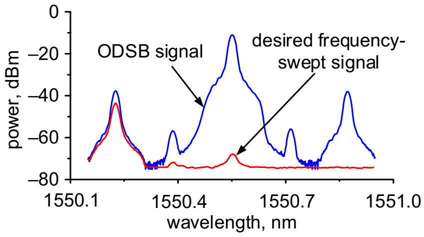

Fig. 2 *Optical spectra of the ODSB and carrier-suppressed single-sideband signals*

Fig. 3 shows the optical spectra of the SUT measured by the proposed MWP-based COSA and APEX 2040 (with 0.04 pm resolution). As can be seen, the optical spectrum of the SUT in a frequency range of over 20 GHz offset the optical carrier is precisely measured using the 10 GHz MZM and RF source, which indicates that the measurement range is doubled (red line in Fig. 3*a*). Benefitting from the high resolution (1.5 MHz in our experiment), the frequency tones around 10 and 20 GHz are clearly observed, as shown as the red lines in Figs. 3*b* and *c*. The measured spectra show that the frequency tones have a frequency spacing of 100 MHz, which is coincided with the electrical multi-tone signal generated by the AWG. It is worth to mention that higher resolution can be achieved by increasing the measurement points and using ultra-narrow-linewidth laser source. Theoretically, a sub-Hz resolution is potentially achievable.

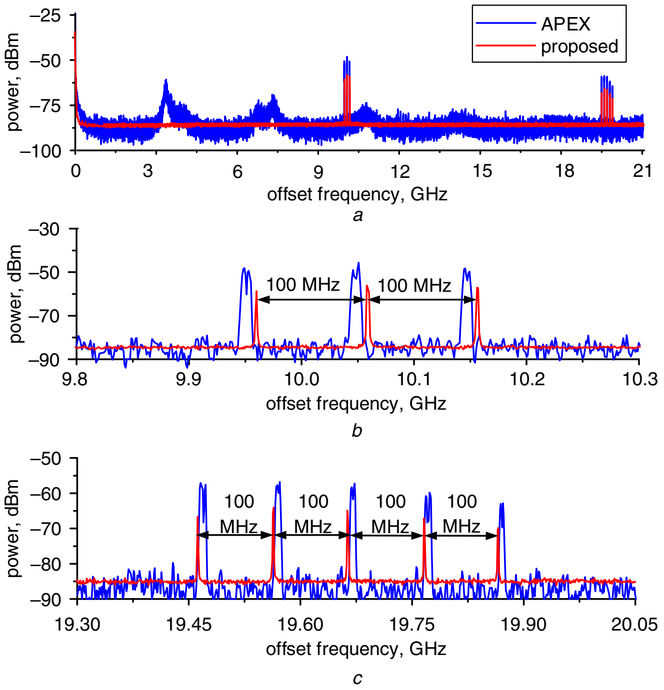

Fig. 3 *Optical spectra of the SUT measured by the proposed COSA and a commercial high-resolution OSA (APEX2040)*

a Full range (0–25 GHz offset)
b Zoom-in spectra around 10 GHz offset
c Zoom-in spectra around 20 GHz offset

As a comparison, the spectrum of the SUT measured by APEX 2040 is also plotted in Fig. 3 (blue lines). As can be seen, the fine structure of the SUT, such as the frequency tones, is observed by both methods. However, the spectrum measured by APEX 2040 contains obvious spurs, which are induced by the relatively small side-mode suppression ratio (SMSR) of the employed WSLS. The spurs would influence the measurement accuracy, especially when measuring weak signals. Benefitting from the large SMSR of the narrow linewidth laser, the influence of the side modes is ignorable in the proposed MWP-based COSA.

Another advantage of the proposed MWP-based COSA is the ultra-high frequency accuracy, which is a great challenge to the COSA based on the WSLS. The poor frequency stability of the WSLS results in peak splitting, as shown as the blue lines in Figs. 3*b* and *c*. Hence, the frequency, power and frequency spacing of the SUT cannot be accurately obtained. It is notable that the power of the spectrum measured by the proposed method is smaller than that measured by the commercial COSA. It is because that the BPDs introduce some conversion loss in the proposed method.

Conclusion: A high-resolution MWP-based COSA having a wideband measurement range was proposed and experimentally demonstrated. The spectrum of a multi-tone-modulated optical signal in a frequency range of over 20 GHz was measured using the 10 GHz components. As compared with the COSA based on WSLS, the proposed MWP-based COSA has advantages in terms of high frequency resolution, high measurement accuracy and excellent frequency stability.

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One or more of the Figures in this Letter are available in colour online.

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