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Ultrahigh-resolution and wideband optical vector analysis for arbitrary responses

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An ultrahigh-resolution and wideband optical vector analyzer (OVA) with the simplest architecture, to the best of our knowledge, is proposed and demonstrated based on chirped optical double-sideband (ODSB) modulation in a single-drive Mach-Zehnder modulator (MZM). To distinguish the magnitude and phase information carried by the two sidebands in the ODSB signal, a two-step measurement, in which biasing, respectively, the MZM at two different points is applied. Because no optical filtering is required in the scheme, the optical carrier can be located at any wavelength that is suitable for accurate measurement, e.g., close to the notch of a notch response or within the passband of a bandpass response, so the proposed OVA has the capability to measure an arbitrary response. An experiment is carried out, which achieves the magnitude and phase responses of a programmable optical processor with bandpass, notch, or falling-edge responses. The measurement bandwidth is 134 GHz, and the measurement resolu-© 2018 Optical Society of America tion is 1.12 MHz.

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High-resolution optical spectral response measurement in both magnitude and phase dimensions is highly desired in the fabrication of high-quality optical components and construction of modern optical information systems [1]. The current optical vector analyzers (OVAs) in the market to achieve the magnitude and phase responses are mainly built based on phase-shift [2] or interferometry approaches [3–5], which have a relatively low spectral resolution because of the poor wavelength accuracy and stability of the wavelength-swept laser sources required in the schemes [6]. To achieve measurements with ultrahigh resolution, OVAs based on optical single-sideband (OSSB) modulation were developed [7–13]. With the high-fineness frequency-swept radio frequency (RF) sources to replace the

wavelength-swept laser sources, the OSSB-based OVA can reach sub-MHz or even sub-Hertz resolution [8], which enables the characterization of high-Q optical devices such as silicon-oninsulator micro-disk or micro-ring chips [14,15], phase-shifted fiber Bragg gratings [16], sampled fiber gratings [17], stimulated Brillouin scattering (SBS)-based filters [18,19], and so on. However, the conventional electro-optical conversion intrinsically generates optical double-sideband (ODSB) modulated signals, so only one sideband is useful for the OSSB-based OVAs, and the other should be suppressed to avoid interference. This places a performance limitation in terms of measurement bandwidth, accuracy, and dynamic range because the methods to generate the OSSB modulation always have relatively small frequency range, low sideband suppression ratio, and considerable high-order sidebands [1]. Another key drawback of the OSSBbased OVAs is their incapability to measure bandpass responses due to the extremely exacerbated carrier-to-sideband ratio because the optical carrier needs to be located outside of the bandpass responses [8].

To overcome these problems, some efforts were devoted to constructing OVAs directly based on ODSB modulation [20-22]. The key to realizing the ODSB-based OVA is to introduce difference to the beat signal of the optical carrier and the left sideband and that of the optical carrier and the right sideband. In [20], an ODSB-based OVA was realized by a two-step measurement together with post-signal processing. Within the two measurement steps, the power ratios of the two first-order sidebands are controlled to be different using a tunable optical filter. Due to the poor wavelength setting accuracy, the employment of a tunable optical filter not only increases the link loss, cost, and operation complexity but also brings in considerable measurement error. As an improvement, we proposed an ODSB-based OVA by shifting the wavelength of the optical carrier using SBS effect [21] or a dual-drive dualparallel Mach-Zehnder modulator (MZM) [22]. Two RF signals with different frequencies are produced by beating the two first-order sidebands and the frequency-shifted carrier at a photodetector (PD), so that the magnitude and phase information carried by the two first-order sidebands can be distinguished in the electrical domain. This approach, however,

requires additional RF sources, an optical frequency shifter, wideband RF mixers, and one more wideband microwave phase-magnitude detector (PMD).

In this Letter, we propose and demonstrate a novel OVA based on chirped double-sideband modulation using a singledrive MZM. To distinguish the magnitude and phase information carried by the two first-order sidebands in the ODSB signal, the measurement is performed twice with two different bias settings of the MZM, which generates two ODSB modulations with different phase relationships between the carrier and sidebands. Based on the two measurements, two complex equations can be established, which are then used to calculate the magnitudes and phases of the two sidebands and further extract the frequency responses of the device under test (DUT). Compared with the OSSB-based OVAs, the measurement range is doubled because both sidebands are used for measurement, and the capability to measure arbitrary optical responses (both notch and bandpass) is enabled; and, as compared with the previously reported ODSB-based OVAs, the system is dramatically simplified because no optical filter and additional RF components are required.

Figure 1 shows the schematic diagram of the proposed OVA based on chirped ODSB modulation. Mathematically, the chirped ODSB signal generated by the single-drive MZM is given by

$$E(t) = A_1 e^{j\pi/2} \exp\left[j(\omega_c - \omega_e)t\right] + (A_0 + A'_0 e^{j\theta}) \exp(j\omega_c t)$$
$$+ A_1 e^{j\pi/2} \exp\left[j(\omega_c + \omega_e)t\right],$$
(1)

where ω_c and ω_e are the angle frequencies of the optical carrier from the tunable laser source (TLS) and the RF signal from the RF source, A_0 and A'_0 are the carrier amplitudes of the upper and lower branches of the MZM, respectively, A_1 is the amplitude of the sidebands, and θ is the phase difference between the upper and lower branches introduced by the DC bias. Because the RF signal is only connected to one arm of the MZM, the change of the bias voltage would only modify the magnitude and phase of the optical carrier. In writing Eq. (1), small signal modulation is assumed, so second- and higher-order sidebands are ignored.

After passing through the DUT, each wavelength component in the optical signal will be modified by the frequency responses of the DUT, so the output signal can be written as

$$\begin{split} E_{\text{DUT}}^{\text{out}}(t) &= H(\omega_{\text{c}} - \omega_{\text{e}})A_{1} \, \mathrm{e}^{j\pi/2} \exp\left[j(\omega_{\text{c}} - \omega_{\text{e}})t\right] \\ &+ H(\omega_{\text{c}})(A_{0} + A_{0}' \mathrm{e}^{j\theta}) \exp(j\omega_{\text{c}}t) \\ &+ H(\omega_{\text{c}} + \omega_{\text{e}})A_{1} \, \mathrm{e}^{j\pi/2} \exp\left[j(\omega_{\text{c}} + \omega_{\text{e}})t\right], \end{split}$$
(2)



Fig. 1. Diagram of the proposed OVA based on chirped ODSB modulation. MZM, Mach–Zehnder modulator; TLS, tunable laser source; DUT, device under test; PD, photodetector; RF, radio frequency; PMD, phase-magnitude detector.

where $H(\omega) = H_{\text{DUT}}(\omega) \cdot H_{\text{sys}}(\omega)$, and $H_{\text{DUT}}(\omega)$ is the complex transmission response of the DUT, and $H_{\text{sys}}(\omega)$ is the transmission function of the system without the DUT. The optical signals in Eq. (2) are then converted into an electrical signal in the PD, so we get

$$i = \eta E_{\text{DUT}}^{\text{out*}} \cdot E_{\text{DUT}}^{\text{out}}$$

= $\eta H^*(\omega_c - \omega_c) H(\omega_c) (A_0 + A'_0 e^{j\theta}) A_1^* e^{-j\pi/2} \exp(j\omega_c t)$
+ $\eta H(\omega_c + \omega_c) H^*(\omega_c) (A_0 + A'_0 e^{j\theta})^* A_1 e^{j\pi/2} \exp(j\omega_c t),$
(3)

where η is the responsivity of the PD. Because $(A_0 + A'_0 e^{j\theta})^* A_1$ and $(A_0 + A'_0 e^{j\theta}) A_1^*$ have the same amplitude but different phase, we can let $e^{j\varphi}$ equal to $\frac{(A_0 + A'_0 e^{j\theta})^* A_1}{(A_0 + A'_0 e^{j\theta}) A_1^*}$. Thus, Eq. (3) can be normalized to

$$i_{\text{norm}} = \frac{i}{\eta (A_0 + A'_0 e^{j\theta}) A_1^*}$$

= $e^{j\varphi} H(\omega_c + \omega_e) H^*(\omega_c) e^{j\pi/2} \exp(j\omega_e t)$
+ $H^*(\omega_c - \omega_e) H(\omega_c) e^{-j\pi/2} \exp(j\omega_e t).$ (4)

The two terms on the right hand of Eq. (4) represent the beat signal of the optical carrier and the left sideband and that of the optical carrier and the right sideband. Because they are of the same frequency, the frequency responses of the DUT at the two wavelengths could not be differentiated directly from Eq. (4). To solve this problem, we adjust the DC bias, which changes θ and further alters φ . Given two values of φ (take φ_1 and φ_2 as examples), two complex equations will be obtained:

$$i_{\text{norm1}} = e^{j\varphi_1} H(\omega_c + \omega_c) H^*(\omega_c) e^{j\pi/2}$$

$$\times \exp(j\omega_e t) + H^*(\omega_c - \omega_e) H(\omega_c) e^{-j\pi/2} \exp(j\omega_e t), \quad \textbf{(5)}$$

$$i_{\text{norm2}} = e^{j\varphi_2} H(\omega_c + \omega_e) H^*(\omega_c) e^{j\pi/2}$$

$$\times \exp(j\omega_{\rm e}t) + H^*(\omega_{\rm c} - \omega_{\rm e})H(\omega_{\rm c})e^{-j\pi/2}\exp(j\omega_{\rm e}t).$$
 (6)

. . .

From Eqs. (5) and (6), the frequency response of the DUT together with the system response can be derived:

$$H(\omega_{\rm c} + \omega_{\rm c}) = \frac{i_{\rm norm1} - i_{\rm norm2}}{e^{j\pi/2} (e^{j\varphi_1} - e^{j\varphi_2}) H^*(\omega_{\rm c})},$$
(7)

$$H(\omega_{\rm c} - \omega_{\rm e}) = \frac{e^{j\varphi_1}(i_{\rm norm1}^* - i_{\rm norm2}^* \cdot e^{j(\varphi_2 - \varphi_1)})}{e^{j\pi/2}(e^{j\varphi_1} - e^{j\varphi_2})H^*(\omega_{\rm c})}.$$
 (8)

The system response can be obtained by using a calibration process, in which the DUT is removed and the output of the MZM is directly connected to the PD. So we get

$$H_{\rm sys}(\omega_{\rm c}+\omega_{\rm c}) = \frac{i_{\rm norm1}^{\rm sys} - i_{\rm norm2}^{\rm sys}}{e^{j\pi/2}(e^{j\varphi_{\rm 1}} - e^{j\varphi_{\rm 2}})H_{\rm sys}^*(\omega_{\rm c})},$$
 (9)

$$H_{\rm sys}(\omega_{\rm c}-\omega_{\rm c}) = \frac{e^{i\varphi_1}(i_{\rm norm1}^{**ys} - i_{\rm norm2}^{**ys} \cdot e^{j(\varphi_2-\varphi_1)})}{e^{j\pi/2}(e^{j\varphi_1} - e^{j\varphi_2})H_{\rm sys}^*(\omega_{\rm c})},$$
 (10)

where i_{norm1}^{sys} and i_{norm2}^{sys} are the photocurrents achieved with different modulator bias settings. Removing the system response from Eqs. (7) and (8), the frequency responses of the DUT at the frequencies of $\omega_c \pm \omega_e$ will be simultaneously obtained:

$$H_{\text{DUT}}(\omega_{\text{c}} + \omega_{\text{e}}) = \frac{H(\omega_{\text{c}} + \omega_{\text{e}})}{H_{\text{sys}}(\omega_{\text{c}} + \omega_{\text{e}})}$$
$$= \frac{i_{\text{norm1}} - i_{\text{norm2}}}{(i_{\text{norm1}}^{\text{sys}} - i_{\text{norm2}}^{\text{sys}}) \cdot H_{\text{DUT}}^{*}(\omega_{\text{c}})}, \quad (11)$$

$$H_{\text{DUT}}(\omega_{\text{c}} - \omega_{\text{e}}) = \frac{H(\omega_{\text{c}} - \omega_{\text{e}})}{H_{\text{sys}}(\omega_{\text{c}} - \omega_{\text{e}})}$$
$$= \frac{i_{\text{norm1}}^* - i_{\text{norm2}}^* \cdot e^{j(\varphi_2 - \varphi_1)}}{(i_{\text{norm1}}^{\text{*sys}} - i_{\text{norm2}}^{\text{*sys}} \cdot e^{j(\varphi_2 - \varphi_1)})H_{DUT}^*(\omega_{\text{c}})},$$
(12)

where $H_{DUT}^*(\omega_c)$ is the response of the DUT at the wavelength of the optical carrier, which is a constant.

In order to demonstrate the feasibility of the scheme, a proofof-concept experiment based on the setup in Fig. 1 is carried out. The parameters of the key devices used in the experiment are listed below. The TLS (Agilent N7714A) has a wavelength tuning range from 1527.6 to 1565.5 nm. The single-drive MZM (EOSPACE, AZ-DV5-40-PFU-SFU-SLB65) has a 5 dB bandwidth of 67 GHz and a half-wave voltage of 2.9 V. An electrical vector network analyzer (EVNA, R&S ZVA67) is employed as the frequency-swept RF source and the PMD. The PD (U2T XPDV3120) has a bandwidth of 70 GHz and a responsivity of 0.5 A/W. In addition, an optical spectrum analyzer (OSA, APEX AP2040D) with a resolution of 5 MHz is employed to monitor the optical spectra. The DUT in the experiment is a programmable optical processor (WaveShaper 4000s), which is configured to have a falling edge and a Hilbert transformation response.

In the experiment, the RF source sweeps from 10 MHz to 67 GHz, and the optical carrier is set to be 1549.51 nm, locating between the falling edge and the Hilbert transformer. The MZM is biased at the positive quadrature point (Q+) in the first measurement step and the negative quadrature point (Q-) in the second step, respectively, so that $\varphi_2 - \varphi_1 = \pi$. The Q+ and Q- bias states of the single-drive MZM can be accurately achieved using a commercially available modulator bias-control circuit. The measured responses are shown in Fig. 2. Figure 2(a)shows the magnitude responses of the OVA system with the DUT and without the DUT when the MZM is biased at the Q+ point, while the corresponding phase responses are shown in Fig. 2(b). Figures 2(c) and 2(d) show the case when the MZM is biased at the Q- point. It should be noted that the start phase in Fig. 2(d) is -37.4 deg, which has a difference of 179.9 deg to that in Fig. 2(b) (142.5 deg), showing that the bias settings of the MZM in the experiment are accurate.

The frequency responses of the DUT are calculated based on the two complex equations in Eqs. (11) and (12) and are shown in Fig. 3. A full measurement range of 134 GHz (corresponding to 1.072 nm in the wavelength domain) has been achieved by the proposed OVA, which is two times the bandwidth of the devices used in the experiment. As the maximum achievable measurement points of the PMD are 60001, the resolution of the proposed OVA reaches 1.12 MHz. In addition, the magnitude and phase responses of the falling edge and Hilbert transformer can be clearly observed, showing that the proposed OVA has the capability to measure arbitrary responses. As a comparison, the magnitude response is also measured by the high-resolution optical spectrum analyzer, with the



Fig. 2. (a) Magnitude and (b) phase responses of the proposed OVA with and without the DUT when the MZM is biased at the Q+ point; (c) and (d) show the case when the MZM is biased at the Q- point.



Fig. 3. (a) Magnitude and (b) phase responses of the DUT measured by the proposed OVA.

result shown as the dashed line in Fig. 3(a). As can be seen, the magnitude response measured by the proposed OVA matches quite well with the one measured by the optical spectrum analyzer. To verify the accuracy of the phase measurement of the proposed OVA, we apply the phase-magnitude relationship of the Hilbert transformer. From Fig. 3(b), there is a 180.5 deg phase shift at around 1549.326 nm, corresponding to ~21 dB notch depth in the magnitude response in theory, which agrees with the measurement result in Fig. 3(a).

Because there is no optical filter in the proposed OVA, the measurable wavelength range is only limited by the wavelength tuning range of the laser source. Figure 4 shows the measurement results when the programmable optical processor is configured to have a 20 dB bandpass response at the center wavelength of 1561.41 nm and a 41 dB notch response at 1532.29 nm.



Fig. 4. Magnitude and phase responses of the DUT at (a) 1561.4 nm and (b) 1532.29 nm.

The magnitude responses measured by the proposed OVA fit quite well with those measured by the high-resolution optical spectrum analyzer. The measured phase responses by the OVA are also shown in Fig. 4. It should be noted that an effective method to enlarge the measurement range is to stitch the responses measured at different wavelengths. The TLS can easily provide a series of carriers at different wavelengths, but the inaccurate frequency spacing between two neighboring carriers would deteriorate the accuracy and resolution when stitching the frequency responses. To avoid the deterioration, optical frequency comb is a promising method due to the fixed frequency spacing [23].

In conclusion, a novel OVA based on chirped double sideband modulation was proposed and demonstrated experimentally. Both the first-order sidebands of the chirped ODSB modulation were used for DUT measurement, which doubled the measurement range. A combined response, including a falling edge and a Hilbert transformer, was successfully measured by the proposed OVA. The measurement bandwidth is 134 GHz, and the measurement resolution is 1.12 MHz. Benefitting from the large dynamic range of the EVNA (about 130 dB), the proposed OVA has a dynamic range of over 80 dB, with the degradation mainly from the insertion loss and conversion loss of the devices. Determined by the linewidth of the TLS, the frequency resolution of the implemented OVA is less than 100 kHz. And the measurement errors of the magnitude and phase are about 0.4 dB and 2 deg, respectively. In addition, Letter

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figuration, large measurement bandwidth, reliable measurement

result, and capability to measure arbitrary responses.

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