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Optical vector analysis based on double-sideband modulation and stimulated Brillouin scattering

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A high-resolution and high-accuracy optical vector analysis based on optical double-sideband modulation and stimulated Brillouin scattering is proposed and experimentally demonstrated. Different from the conventional OVA based on optical single-sideband modulation, in which the measurement range is limited by the bandwidth of the microwave and optoelectronic components, and the measurement accuracy is restricted by the high-order sidebands, the proposed technique measures the magnitude and phase responses by making use of both ± 1 st-order sidebands without spectrum response aliasing. As a result, the measurement range is doubled, and the high-order, sideband-induced errors only appear at specific frequencies that are predictable and removable. A proof-of-concept experiment is carried out. The transmission response of a fiber Bragg grating, in a range of 80 GHz, is measured with a resolution of less than 667 kHz by using 40 GHz microwave components. © 2016 Optical Society of America

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The measurement of magnitude and phase responses of an optical component is essential for both device fabrication and system design, which demands optical vector analysis (OVA) with wide bandwidth and high resolution. Previously, two main methods were proposed to measure the optical frequency response, i.e., the modulation phase-shift approach [1] and the interferometry method [2], both of which rely on wavelength sweeping of a laser source, thus resulting in a poor resolution (typically several hundreds of MHz). To perform ultrahigh-resolution measurement, an approach based on optical single-sideband (OSSB) modulation was proposed [3–14]. The key to implementing the OSSB-based OVA is to realize OSSB modulation with large modulation bandwidth, high modulation linearity, and wide operational wavelength range. A number of techniques have been reported to implement the OSSB modulation, but few of them can meet the above requirements. In addition, the OSSB-based OVA can only make use of one

sideband to scan one side, which limits the measurement range to the bandwidth of the microwave and optoelectronic components used in the system (typically less than 40 GHz). Furthermore, the OSSB modulation would inevitably stimulate high-order sidebands, especially when the phase modulation index is large, which could introduce considerable measurement errors [8].

Recently, we have proposed a method to measure the optical magnitude response based on optical double-sideband (ODSB) modulation [15]. As compared with the OSSB modulation, ODSB modulation is wideband, simple, and efficient. However, when a conventional ODSB signal is sent to a photodetector (PD), the ± 1 st-order sidebands are beaten with the optical carrier, generating RF signals with the same frequency, by which the frequency responses carried by the two sidebands cannot be differentiated. To solve this spectrum response aliasing problem, in [15] the optical carrier is divided into two branches, in one of which a frequency shift is introduced. When the two sidebands, after propagating through the optical device-under-test (DUT) and the frequency-shifted optical carrier, are combined and beaten at a PD, two different frequency components are generated, from which the magnitude information carried by different sidebands is extracted without aliasing. However, this approach cannot be utilized to measure phase response because of the large phase noise introduced by the optical path separation.

In this Letter, we propose and demonstrate a novel ODSB-based OVA by which both magnitude and phase responses can be measured. The key component in the proposed scheme is a dual-parallel Mach–Zehnder modulator (DP-MZM), which generates two sweeping sidebands in one sub-MZM and two wavelength-fixed sidebands in the other sub-MZM. Then, stimulated Brillouin scattering (SBS) is introduced to suppress one wavelength-fixed sideband and enhance the other wavelength-fixed sideband, so the remainder can serve as the frequency-shifted carrier. When the signal is sent to a PD, the two sweeping sidebands are beaten, respectively, with the frequency-shifted carrier, generating RF signals with different frequencies. The phase response can be accurately measured because the frequency-shifted carrier and the sweeping sidebands are not physically separated. Since the frequencies of the useful RF signals are not integral multiples of that of

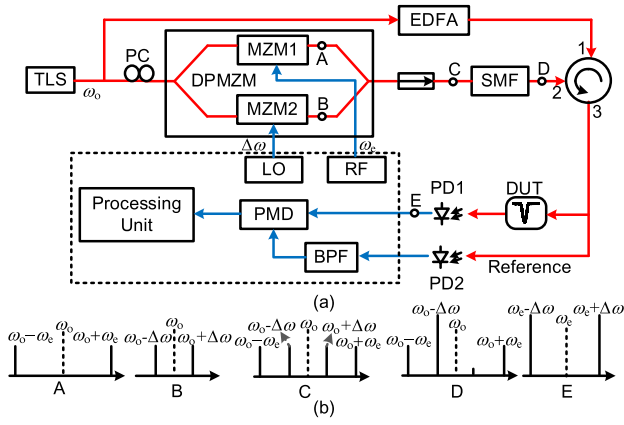


Fig. 1. (a) Schematic diagram of the proposed ODSB-based OVA scheme. (b) Spectra of the signals in different points. TLS, tunable laser source; PC, polarization controller; MZM, Mach-Zehnder modulator; EDFA, erbium-doped fiber amplifier; SMF, single-mode fiber; DUT, device under test; PD, photodetector; BPF, bandpass filter; PMD, phase-magnitude detector; RF, radio frequency; LO, local oscillator.

the modulation signal, the frequency responses extracted from them are almost immune to the measurement errors introduced by the higher-order sidebands, which is a serious problem in the OSSB-based OVA.

The schematic diagram of the proposed ODSB-based OVA scheme is shown in Fig. 1(a). A lightwave with an angular frequency of ω_o is generated by a tunable laser source (TLS) and then divided into two portions by an optical splitter. One portion amplified by an erbium-doped fiber amplifier (EDFA) is served as the SBS pump signal. The other part, in the lower path, incorporates a DP-MZM, which consists of two sub-MZMs, i.e., MZM1 and MZM2. In MZM1, the optical carrier is modulated by a frequency-swept RF signal with a frequency of ω_e , producing two sweeping sidebands with frequencies of $\omega_o - \omega_e$ and $\omega_o + \omega_e$. In MZM2, the optical carrier is modulated by a local oscillator (LO) signal with a fixed frequency of $\Delta\omega$, which equals the Brillouin frequency shift, to produce two wavelength-fixed sidebands with frequencies of $\omega_o - \Delta\omega$ and $\omega_o + \Delta\omega$. As a result, the output of the DP-MZM is the combination of the sweeping sidebands and wavelength-fixed sidebands. The optical field can be written as

$$E(\omega) = a_{-1}\delta[\omega - (\omega_o - \omega_e)] + a_{+1}\delta[\omega - (\omega_o + \omega_e)] + b_{-1}\delta[\omega - (\omega_o - \Delta\omega)] + b_{+1}\delta[\omega - (\omega_o + \Delta\omega)], \quad (1)$$

where a_{-1} , a_{+1} , b_{-1} and b_{+1} are the complex amplitudes of the two sweeping sidebands and the two wavelength-fixed sidebands, respectively.

When this optical signal goes through a length of single-mode fiber (SMF), the -1st-order wavelength-fixed sideband is amplified, and the +1st-order sideband is suppressed by SBS excited in an SMF. Thus, the carrier-shifted ODSB signal is generated, given by

$$E_p(\omega) = a_{-1}\delta[\omega - (\omega_o - \omega_e)] + a_{+1}\delta[\omega - (\omega_o + \omega_e)] + B_{-1}\delta[\omega - (\omega_o - \Delta\omega)], \quad (2)$$

where B_{-1} is the complex amplitude of the frequency-shifted carrier. Then, the optical signal is divided into two paths.

In the measurement path, a DUT is inserted. The two sweeping sidebands and frequency-shifted carrier of the carrier-shifted ODSB signal undergo magnitude and phase changes according to the transmission function of the DUT. The optical signal after DUT can be expressed as

$$E_m(\omega) = E_p(\omega) \cdot H(\omega) = a_{-1}H(\omega_o - \omega_e)\delta[\omega - (\omega_o - \omega_e)] + a_{+1}H(\omega_o + \omega_e)\delta[\omega - (\omega_o + \omega_e)] + B_{-1}H(\omega_o - \Delta\omega)\delta[\omega - (\omega_o - \Delta\omega)], \quad (3)$$

where $H(\omega) = H_{\text{sys}}(\omega) \cdot H_{\text{DUT}}(\omega)$, $H_{\text{sys}}(\omega)$ and $H_{\text{DUT}}(\omega)$ are the transmission functions of the measurement system and the DUT, respectively.

After square-law detection in a PD (PD1), a photocurrent carrying the spectral responses on both sides of the optical carrier is achieved, written as

$$i_m(\omega_e - \Delta\omega) = \eta a_{-1}^* B_{-1} H^*(\omega_o - \omega_e) H(\omega_o - \Delta\omega), \quad \text{if } \omega_e > \Delta\omega \\ i_m(\Delta\omega - \omega_e) = \eta a_{-1} B_{-1}^* H(\omega_o - \omega_e) H^*(\omega_o - \Delta\omega), \quad \text{if } \omega_e < \Delta\omega \\ i_m(\omega_e + \Delta\omega) = \eta a_{+1} B_{-1}^* H(\omega_o + \omega_e) H^*(\omega_o - \Delta\omega), \quad (4)$$

where η is the responsivity of PD1.

In the reference path, the optical signal is directly converted into a photocurrent by a second PD (PD2). The corresponding components are used as reference signals. According to the reference signals, the magnitude and phase of the frequency components from PD1 can be extracted.

To eliminate the influence of the measurement system, a calibration in which the two test ports are directly connected is performed. In the calibration, the components having frequencies of $\omega_e + \Delta\omega$, $|\omega_e - \Delta\omega|$ are obtained, which can be expressed as

$$i_{\text{cal}}(\omega_e - \Delta\omega) = \eta a_{-1}^* B_{-1} H_{\text{sys}}^*(\omega_o - \omega_e) H_{\text{sys}}(\omega_o - \Delta\omega), \quad \text{if } \omega_e > \Delta\omega \\ i_{\text{cal}}(\Delta\omega - \omega_e) = \eta a_{-1} B_{-1}^* H_{\text{sys}}(\omega_o - \omega_e) H_{\text{sys}}^*(\omega_o - \Delta\omega), \quad \text{if } \omega_e < \Delta\omega \\ i_{\text{cal}}(\omega_e + \Delta\omega) = \eta a_{+1} B_{-1}^* H_{\text{sys}}(\omega_o + \omega_e) H_{\text{sys}}^*(\omega_o - \Delta\omega). \quad (5)$$

According to Eqs. (4) and (5), the transmission function of the DUT can be achieved, given by

$$H_{\text{DUT}}(\omega_o - \omega_e) = \frac{i_m^*(\omega_e - \Delta\omega)}{i_{\text{cal}}^*(\omega_e - \Delta\omega) H_{\text{DUT}}^*(\omega_o - \Delta\omega)}, \quad \text{if } \omega_e > \Delta\omega \\ H_{\text{DUT}}(\omega_o - \omega_e) = \frac{i_m(\Delta\omega - \omega_e)}{i_{\text{cal}}(\Delta\omega - \omega_e) H_{\text{DUT}}^*(\omega_o - \Delta\omega)}, \quad \text{if } \omega_e < \Delta\omega \\ H_{\text{DUT}}(\omega_o + \omega_e) = \frac{i_m(\omega_e + \Delta\omega)}{i_{\text{cal}}(\omega_e + \Delta\omega) H_{\text{DUT}}^*(\omega_o - \Delta\omega)}, \quad (6)$$

where $H_{\text{DUT}}^*(\omega_o - \Delta\omega)$ is the response of the frequency-shifted carrier, which is a constant.

Sweeping the frequency of the RF signal, the spectral responses of the DUT on both sides of the optical carrier, i.e., $H_{\text{DUT}}(\omega_o - \omega_e)$ and $H_{\text{DUT}}(\omega_o + \omega_e)$, are obtained. It should be noted that the ω_e components beaten by the n th and $(n \pm 1)$ th-order sidebands, which contribute significantly to the measurement errors in the OSSB-based OVA, have no influence on the measurement accuracy, since the spectral

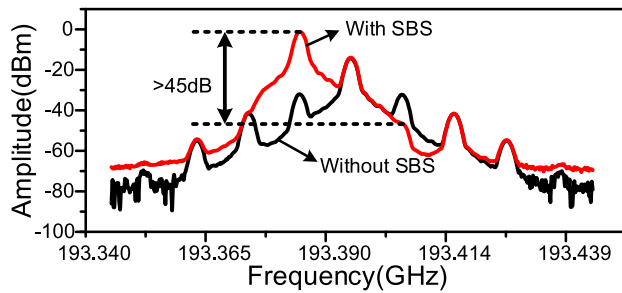


Fig. 2. Optical spectra of the optical signal modulated by the LO signal (black solid line) and the one processed by the SBS in the SMF (red solid line).

responses are extracted from the $|\omega_c - \Delta\omega|$ and $\omega_c + \Delta\omega$ components.

A proof-of-concept experiment based on the setup shown in Fig. 1(a) is carried out. An optical carrier is generated by a TLS (Agilent N7714A), which is split into two branches. One amplified by an EDFA (Amonics, Inc.) serves as the pumping signal to excite the SBS in an 8 km SMF. The other one is modulated by a RF signal and a LO signal from a vector network analyzer (VNA, R&S ZVA67) at a DP-MZM (Fujitsu) with a bandwidth of 40 GHz and a half-wave voltage of 1.75 V. According to the Brillouin frequency shift of the 8 km SMF, the frequency of the LO signal is set at 10.845 GHz. Then, the optical signal is processed by the SBS in the 8 km SMF, and the carrier-shifted ODSB signal is thus obtained. The ODSB signal is divided into two paths. In the measurement path, the optical signal, propagating through a fiber Bragg grating (FBG) [i.e., DUT], is converted into a photocurrent carrying the spectral responses by a 50 GHz PD (Finisar XPD2150R). In the reference path, another 50 GHz PD is inserted. Referred by the photocurrent in the reference path, the VNA extracts the magnitude and phase of the photocurrent in the measurement path. The optical spectra are measured by an optical spectrum analyzer (OSA) (Yokogawa AQ6370C) with a resolution of 0.02 nm.

Figure 2 shows the optical spectra of the optical signal modulated by the LO signal and the one processed by the SBS in the SMF. As can be seen, the -1st-order sideband is amplified while the +1st-order sideband is suppressed by the SBS excited in the SMF. The sideband suppression ratio (SSR) is larger than 45 dB, so the residual +1st-order sideband is too weak to affect the measurement accuracy.

In the experiment, the magnitude and phase responses of the FBG under test are one by one mapped in three segments by detecting the components with frequencies of $\omega_c - \Delta\omega$ ($\omega_c > \Delta\omega$), $\Delta\omega - \omega_c$ ($\omega_c < \Delta\omega$), and $\omega_c + \Delta\omega$. Then, stitching the measured responses together, the spectral responses in a frequency range of 80 GHz are achieved, as shown in Fig. 3. The three segments of measurement are separated by the dashed lines in Fig. 3, and every segment contains 60001 points, so the resolutions are 486, 182, and 667 kHz from left to right, respectively. The magnitude of the FBG measured by an amplified spontaneous emission (ASE) source and an OSA is also plotted in Fig. 3(a). By employing the proposed approach, a notch depth of 30 dB can be obtained, while only a 20 dB notch depth can be measured by the OSA, indicating that the proposed ODSB-OVA has a larger dynamic range. It should be

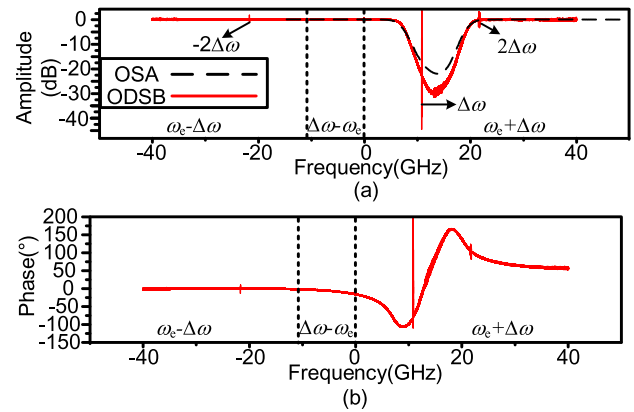


Fig. 3. (a) Magnitude and (b) phase responses measured by the proposed ODSB-based OVA.

noted that there are several spikes in the measured responses. This is because the existence of the original optical carrier would lead to the generation of $n\omega_c$ and $n\omega_c \pm \Delta\omega$ components (n is an integer). When $\omega_c \pm \Delta\omega = n\omega_c$ or $n\omega_c \pm \Delta\omega$, two or more components have the same frequency and their vectorial sum would generate extraordinary points in the measurement results. Since these points are predictable, they can be simply eliminated in the data processing stage.

In conclusion, a novel approach to performing a high-resolution and high-accuracy OVA based on ODSB modulation and SBS was proposed and experimentally demonstrated. Both ± 1 -st-order sidebands of the ODSB signal are used to measure the magnitude and phase responses, which doubles the measurement range. By using 40 GHz bandwidth microwave or optoelectronic devices, the transmission response of a FBG in the range of 80 GHz was measured with a resolution less than 667 kHz.

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REFERENCES

1. T. Niemi, M. Uusimaa, and H. Ludvigsen, *IEEE Photon. Technol. Lett.* **13**, 1334 (2001).
2. G. D. VanWiggeren, A. R. Motamedi, and D. M. Baney, *IEEE Photon. Technol. Lett.* **15**, 263 (2003).
3. E. Voges, O. Ostwald, B. Schiek, and A. Neyer, *IEEE J. Quantum Electron.* **18**, 124 (1982).
4. J. E. Román, M. Y. Frankel, and R. D. Esman, *Opt. Lett.* **23**, 939 (1998).
5. T. Kawanishi, T. Sakamoto, and M. Izutsu, *IEICE Electron. Express* **3**, 34 (2006).
6. M. Sagues and A. Loayssa, *Opt. Express* **18**, 17555 (2010).
7. Z. Z. Tang, S. L. Pan, and J. P. Yao, *Opt. Express* **20**, 6555 (2012).
8. M. Xue, S. L. Pan, X. W. Gu, and Y. J. Zhao, *J. Opt. Soc. Am. B* **30**, 928 (2013).
9. M. Xue, S. Pan, C. He, R. Guo, and Y. Zhao, *Opt. Lett.* **38**, 4900 (2013).

10. C. G. Zhu, J. Chang, P. P. Wang, W. Wei, S. S. Zhang, Z. Liu, and G. D. Peng, *Opt. Express* **21**, 31540 (2013).
11. M. Wang and J. P. Yao, *IEEE Photon. Technol. Lett.* **25**, 753 (2013).
12. M. Xue, S. Pan, and Y. Zhao, *Opt. Lett.* **39**, 3595 (2014).
13. W. Li, W. T. Wang, L. X. Wang, and N. H. Zhu, *IEEE Photon. J.* **6**, 7901108 (2014).
14. M. Xue, S. L. Pan, and Y. J. Zhao, *Opt. Lett.* **40**, 569 (2015).
15. T. Qing, M. Xue, M. H. Huang, and S. L. Pan, *Opt. Lett.* **39**, 6174 (2014).