Optical spectral response measurement based on optical single-sideband modulation with doubled measurement range

Min Xue, Shilong Pan[✉] and Yongjiu Zhao

Accurate measurement of the optical magnitude and phase responses based on optical single-sideband (OSSB) modulation with doubled measurement range is proposed and demonstrated. In the scheme, an optical carrier and a second-order sideband are generated by an RF signal at an OSSB modulator consisting of a Mach–Zehnder modulator and an optical bandpass filter. After the optical device under test, the signal is sent to a photodetector, generating a frequency-doubled microwave signal, which is mixed with the RF signal from the transmitter to generate another fundamental frequency signal for phase and magnitude extraction. As a result, the measurement range of the OSSB-based optical vector analysers is doubled. In a proof-of-concept experiment, the magnitude and phase responses of a fibre Bragg grating are accurately measured.

Introduction: In emerging applications such as on-chip optical signal processing [1], optical storage based on slow light [2], high-precision optical sensing [3], and optical devices which have the capability to manipulate the optical spectrum with high finesse are highly desired. The Q value of the state-of-the-art optical whispering-gallery-mode resonator is as high as 6×10^{10} (corresponding to a 3 dB bandwidth of 3 kHz at 1550 nm) [4] and the bandwidth of the fibre Bragg gratings (FBGs) can be as narrow as 9 MHz [5]. In order to extract the spectral responses, including magnitude and phase responses, of such devices, optical vector analysers (OVAs) which can characterise optical devices with ultra-high resolution are required. The conventional OVAs are based on phase-shifted approach [6] or interferometry method [7], in which the wavelength-swept signal is generated by a tunable laser source (TLS). Restricted by the limited wavelength accuracy of the TLS, the resolution of these OVAs is generally larger than 1.6 pm, which cannot support the characterisation of high-Q devices.

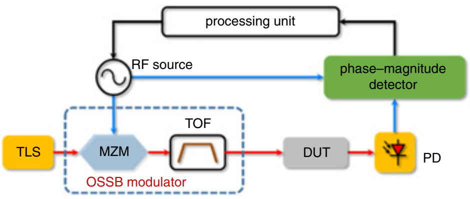

Fig. 1 *Configuration of proposed OVA. TLS, tunable laser source; MZM, Mach–Zehnder modulator; TOF, tunable optical filter; DUT, device under test; and PD, photodetector*

To characterise the spectral responses of the optical devices with ultra-high resolution, optical single-sideband (OSSB) modulation-based OVAs were developed [8–11]. Benefiting from the high-resolution microwave frequency sweeping and accurate microwave phase/magnitude detection, a measurement resolution of tens of kilohertz has been achieved experimentally [9]. However, the measurement range of this kind of OVA is restricted mainly by the small bandwidth of the electro-optic modulators (usually <40 GHz). Previously, we have proposed a method to boost the measurement range using an optical frequency comb [10]. Although very large measurement range was achieved, the operation is relatively complex since a high roll-off tunable optical filter (TOF) is needed to select each comb line from the optical frequency comb.

In this Letter, a novel OSSB-based OVA, which can achieve a measurement range that is two times the bandwidth of the electro-optic modulator (EOM), is proposed and demonstrated. If the proposed technique is applied in the OVA in [10], the required comb spacing can be doubled, so the comb-line selection can be easier and more efficient.

Fig. 1 shows the schematic diagram of the proposed OVA. A lightwave with a fixed wavelength is generated by a TLS, which is modulated by a swept RF frequency at a single-drive Mach–Zehnder modulator (MZM). Biasing the MZM at the maximum transmission point (MATP), an optical double-sideband (ODSB) signal with all odd-order sidebands eliminated is generated. Removing one second-order sideband (taking the second-order sideband for example) by a TOF, an OSSB signal is thus obtained, which can be written as

$$E_{\text{in}}(\omega) = A_0 \cdot \delta(\omega - \omega_o) + A_{+2} \cdot \delta[\omega - (\omega_o + 2\omega_e)] \quad (1)$$

where A_0 and A_{+2} are the complex amplitudes of the optical carrier and the remaining second-order sideband, respectively, and ω_o and ω_e denote the optical carrier frequency and the swept RF frequency.

When propagating through an optical device under test (DUT), the optical carrier and the remaining second-order sideband are changed. The changed optical signal can be expressed as

$$E_{\text{out}}(\omega) = A_0 H(\omega_o)\delta(\omega - \omega_o) + A_{+2}H(\omega_o + 2\omega_e)\delta[\omega - (\omega_o + 2\omega_e)] \quad (2)$$

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

A photodetector (PD) is connected to convert the optical signal into the electrical domain. The obtained electrical field can be expressed as

$$i(2\omega_e) = \eta A_{+2} A_0^* H(\omega_o + 2\omega_e) H^*(\omega_o) \quad (3)$$

where η represents the PD responsivity.

The transmission function of the measurement system can be obtained by connecting the two test ports of the proposed OVA directly, by which $H_{\text{ODUT}}(\omega) = 1$. The obtained photocurrent is

$$i_{\text{sys}}(2\omega_e) = \eta A_{+2} A_0^* H_{\text{sys}}(\omega_o + 2\omega_e) H_{sys}^*(\omega_o) \quad (4)$$

From (3) and (4), the transmission function of the optical DUT can be achieved

$$H_{\text{DUT}}(\omega_o + 2\omega_e) = \frac{i(2\omega_e) H_{\text{ODUT}}^*(\omega_o)}{i_{\text{sys}}(2\omega_e)} \quad (5)$$

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

In (5), $i(2\omega_e)$ and $i_{\text{sys}}(2\omega_e)$ are complex signals, so an electrical phase and magnitude detector driven by a $2\omega_e$ reference signal is required to extract the phase and magnitude information carried by them. The high-frequency electrical phase and magnitude detector, however, is always costly and has poor performance. To solve this problem, we mix the frequency-doubled signal from the PD with the RF signal from the microwave source, performing equivalent frequency dividing. The obtained signal has a frequency of ω_e, which can then led to a low-frequency phase and magnitude detector referenced by the swept RF frequency for phase and magnitude information extraction.

The proposed OVA illustrated in Fig. 1 is constructed and used to characterise an FBG. A light wave at 1549.23 nm is generated by a TLS (Agilent N7714A), and sent to MZM driven by an RF signal from a 67 GHz vector network analyser (VNA, R&S ZVA67). The modulator is a single-drive $LiNbO_3$ modulator (Fujitsu FTM7938EZ) which has a 3 dB bandwidth of ~25 GHz. A modulator bias controller (MBC, YYLabs Inc.) is used to ensure that the MZM is biased at the MATP. A TOF (Finisar WaveShaper4000s) is applied to remove one second-order sideband. An FBG fabricated by TeraXion Inc. is used as an optical DUT. Leading the optical signal after the optical DUT to a 50 GHz PD (U2T XPDV2120R), a photocurrent is obtained, which is then sent to the equivalent frequency divider and the phase-magnitude detector in the VNA. An optical spectrum analyser (Yokogawa AQ6370C) is used to measure the optical spectra.

Fig. 2 shows the optical spectra of the ODSB signal output from the MZM biased at the MATP and the OSSB signal filtered by the TOF when a 10 GHz RF signal is applied. As can be seen, the unwanted sideband is significantly suppressed, and the optical carrier is only slightly attenuated even the slope of the filter is not steep.

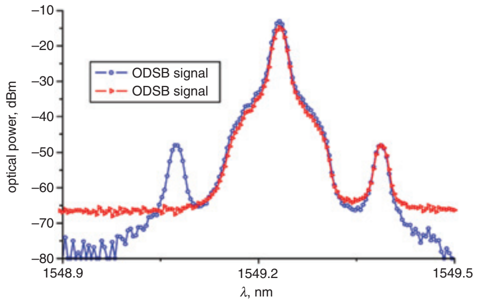

Fig. 2 *Optical spectra of ODSB signal with all odd-order sidebands suppressed and OSSB signal after TOF*

Fig. 3 illustrates the optical spectral responses of the FBG measured by the proposed OVA and a commercial OVA (LUNA OVA5000). As can be seen, by applying the proposed OVA, the optical spectral responses of the FBG in 10–50 GHz offset optical carrier are accurately measured using a 25 GHz MZM (red line), indicating that the measurement range can be much larger than the bandwidth of the EOM. To verify the accuracy of the measurement results, the FBG is also measured by a commercial OVA. The magnitude and phase responses with a resolution of 315.5 MHz are obtained. The measured results are plotted as the blue hollow circles in Fig. 3. As can be seen, the optical spectral responses measured by both OVAs agree very well. It is worth noting that the resolution of our OVA is hundreds of times better than that of the commercial OVA, which is much more accurate when measuring high-finesse optical devices [9].

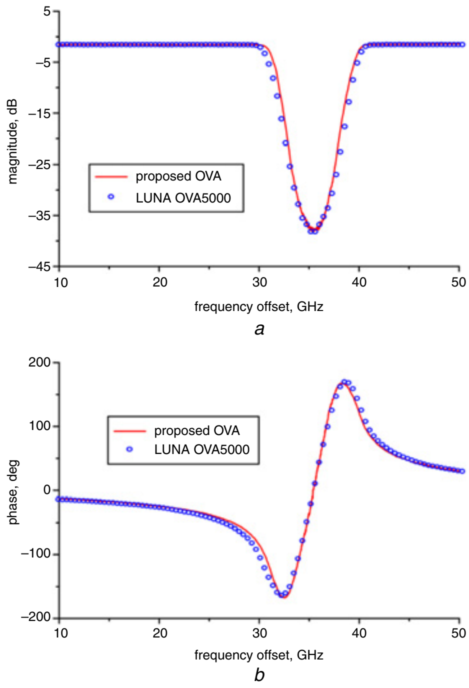

Fig. 3 *Optical spectral responses of FBG measured by proposed OVA and commercial OVA (LUNA OVA5000)*

a Measured magnitude responses
b Measured phase responses

Conclusion: An OSSB-based OVA having a wide measurement range was proposed and experimentally demonstrated. The spectral responses of an FBG in a large frequency range (10–50 GHz offset the optical carrier) were measured using a 25 GHz MZM, which agree well with those measured by a commercial OVA.

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

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