Measurement of optical magnitude response based on double-sideband modulation

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A novel approach to perform high-resolution optical magnitude response measurements, using optical double-sideband (ODSB) modulation, is proposed and experimentally demonstrated. As compared with a conventional optical single-sideband modulation-based optical magnitude response measurement, the proposed method based on ODSB modulation features not only simple configuration and doubled measurement range, but also immunity to modulation nonlinearity. A proof-of-concept experiment is carried out. The magnitude response of a fiber Bragg grating (FBG), in the range of 40 GHz, was measured with a resolution of 10 MHz, by using a 20 GHz microwave signal source.

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The rapid development of photonic systems requires high speed and accurate measurement, of the frequency response of optical devices, with a large measurement range. The magnitude response is one of the key parameters for an optical device under test (DUT). Several methods were proposed to measure the magnitude response, such as the modulation phase-shift approach [1], and the interferometry method [2], but the two methods rely on a wavelength scan of a laser source. Owing to the low wavelength accuracy and poor wavelength stability of typical laser sources, the resolution of the magnitude response measurement schemes, based on the two methods, could not be high (typically several hundreds of MHz). To solve this problem, the method based on optical single-sideband (OSSB) modulation was proposed [3–12], which has much higher resolution (up to 78 kHz in [7]), and better stability. However, there are several limitations associated with the OSSB-based approach. For instance, in the OSSB-based approach, implementation of the OSSB modulation is critical, which should have a broad electrical bandwidth, high modulation linearity, and a large operational wavelength range [8]. In addition, the OSSB-based frequency sweeping can only scan one side, so the measurement range is limited by the bandwidth of the microwave synthesizer, electro-optic modulator, and photodetector (PD; usually less than 40 GHz) [9], or the measurement is time consuming.

In this Letter, we propose, for the first time to the best of our knowledge, a novel approach to perform an optical magnitude response measurement, using optical double-sideband (ODSB) modulation. As compared with OSSB modulation, ODSB modulation is simple, wideband, and efficient. Because both sidebands are utilized simultaneously, the measurement range is doubled. More importantly, the modulation nonlinearity, which is a serious problem in an OSSB-based optical response measurement, will not introduce any measurement error. In addition, similarly to the OSSB-based approach, the frequency scan and magnitude information extraction are implemented in the electrical domain, so high measurement resolution is preserved.

A schematic diagram of the proposed optical magnitude response measurement scheme, using carrier-suppressed ODSB modulation, is shown in Fig. 1(a). An optical carrier from a laser diode (LD) is divided into two branches. One portion is modulated by a sweeping RF signal at a Mach–Zehnder modulator (MZM), which generates a carrier-suppressed ODSB signal. Then, the double-sideband signal is injected into a DUT, in which the +1st- and −1st-order sidebands undergo different magnitude responses. The other part of the optical signal passes through an acousto-optic modulator, to have its frequency shifted by an angular frequency of $\Delta\omega$. The two signals from the two paths are combined, and then beat at a PD. After square-law detection in the PD, two different frequency components are generated. Then, the magnitude information of different frequency components is extracted by an electrical spectrum analyzer (ESA). By scanning the frequency of the RF signal, the magnitude response of the DUT, in both sides of the optical carrier, can be obtained.

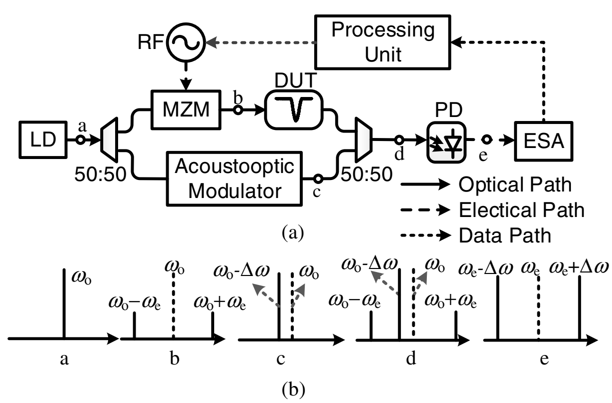

Fig. 1. (a) Schematic diagram of the proposed optical magnitude response measurement scheme, using ODSB modulation; (b) spectra of the signals in different points; DUT, device under test; ESA, electrical spectrum analysis; LD, laser diode; MZM, Mach–Zehnder modulator; PC, polarization controller; PD, photodetector; RF, radio frequency.

Mathematically, the carrier-suppressed ODSB signal generated by the MZM can be written as

$$E_{\mathrm{DSB}}^{\mathrm{in}}(t) = \exp(i\omega_0 t)\{\exp(i\beta \cos \omega_e t) + \exp(i\beta \cos \omega_e t + i\pi)\}, \quad (1)$$

where ω_o and ω_e are the angular frequencies of the optical signal and the RF signal, respectively; $\beta = \pi V/V_\pi$ is the phase modulation index; V is the magnitude of the RF signal; and V_π is the half-wave voltage of the MZM. Based on the Jacobi–Anger expansion, the signal in Eq. (1) can be rewritten as

$$E_{\mathrm{DSB}}^{\mathrm{in}}(t) = \sum_{n=-\infty}^{\infty} \{J_n(\beta) i^n [1 + (-1)^{n+1}] \exp[i(\omega_o + n\omega_e)t]\}, \quad (2)$$

where $J_n(\beta)$ is the nth-order Bessel function of the first kind. The Fourier transform of the signal in Eq. (2) is

$$E_{\mathrm{DSB}}^{\mathrm{in}}(\omega) = \sum_{n=-\infty}^{\infty} \{2\pi i^n [1 + (-1)^{n+1}] J_n(\beta) * \delta[\omega - (\omega_o + n\omega_e)]\}. \quad (3)$$

In the DUT, the magnitude of the sidebands would be changed, according to the response of the DUT

$$\begin{aligned} E_{\mathrm{DSB}}^{\mathrm{out}}(\omega) &= E_{\mathrm{DSB}}^{\mathrm{in}}(\omega) \cdot H(\omega) \\ &= \sum_{n=-\infty}^{\infty} \{2\pi i^n [1 + (-1)^{n+1}] J_n(\beta) H(\omega_o + n\omega_e) \\ &\quad * \delta[\omega - (\omega_o + n\omega_e)]\}, \end{aligned} \quad (4)$$

where $H(\omega)$ is the transmission response of the DUT. After the reverse Fourier transform of $E_{\mathrm{DSB}}^{\mathrm{out}}(\omega)$, we obtain

$$E_{\mathrm{DSB}}^{\mathrm{out}}(t) = \sum_{n=-\infty}^{\infty} \{i^n [1 + (-1)^{n+1}] J_n(\beta) H(\omega_o + n\omega_e) \exp[i(\omega_o + n\omega_e)t]\}. \quad (5)$$

After combined with the frequency-shifted signal in the lower branch, the mixed signal can be written as

$$\begin{aligned} E_{\mathrm{mix}}(t) &= \sum_{n=-\infty}^{\infty} \{i^n [1 + (-1)^{n+1}] J_n(\beta) H(\omega_o + n\omega_e) \\ &\quad \times \exp[i(\omega_o + n\omega_e)t]\} \\ &\quad + \exp[i(\omega_o - \Delta\omega)t + i\phi] \\ &= 2iJ_1(\beta) H(\omega_o + \omega_e) \exp[i(\omega_o + \omega_e)t] \\ &\quad - 2iJ_{-1}(\beta) H(\omega_o - \omega_e) \exp[i(\omega_o - \omega_e)t] \\ &\quad + \exp[i(\omega_o - \Delta\omega)t + i\phi] + E_{\mathrm{other}}, \end{aligned} \quad (6)$$

where ϕ is the phase difference between the two branches; and E_{other} contains all the high-order terms. After square-law detection in the PD, we obtain

$$\begin{aligned} I_{\mathrm{PD}}(t) &= \eta E_{\mathrm{mix}}(t) \cdot E_{\mathrm{mix}}^*(t) \\ &= 2\eta \mathrm{Re}\{-2iJ_{-1}(\beta) H(\omega_o - \omega_e) \exp[-i(\omega_e - \Delta\omega)t - i\phi] \\ &\quad + 2iJ_1(\beta) H(\omega_o + \omega_e) \exp[i(\omega_e + \Delta\omega)t - i\phi]\} + I_{\mathrm{other}}, \end{aligned} \quad (7)$$

where η is the responsivity of the PD; and I_{other} contains all the other frequency components. To simplify the analysis, Eq. (7) can be represented in a complex exponential form, i.e.,

$$\begin{aligned} I_{\mathrm{PD}}(t) &= 2\eta\{2iJ_1(\beta) H(\omega_o - \omega_e) \exp[-i(\omega_e - \Delta\omega)t - i\phi] \\ &\quad + 2iJ_1(\beta) H(\omega_o + \omega_e) \exp[i(\omega_e + \Delta\omega)t - i\phi]\} + I_{\mathrm{other}}. \end{aligned} \quad (8)$$

Because the ESA is set to extract only the magnitude information of the components, with frequencies of $\omega_e + \Delta\omega$ and $\omega_e - \Delta\omega$, the higher-frequency components can be ignored, so we have

$$I_{\mathrm{PD},-1} = 4\eta i J_1(\beta) H(\omega_o - \omega_e) \exp[-i(\omega_e - \Delta\omega)t - i\phi], \quad (9a)$$

$$I_{\mathrm{PD},+1} = 4\eta i J_1(\beta) H(\omega_o + \omega_e) \exp[i(\omega_e + \Delta\omega)t - i\phi]. \quad (9b)$$

From Eqs. (9a) and (9b), we can obtain

$$|H(\omega_o - \omega_e)| = \frac{|I_{\mathrm{PD},-1}|}{4\eta J_1(\beta)}, \quad (10a)$$

$$|H(\omega_o + \omega_e)| = \frac{|I_{\mathrm{PD},+1}|}{4\eta J_1(\beta)}, \quad (10b)$$

where $|H(\omega_o - \omega_e)|$ is the magnitude response of the DUT obtained by the −1st sideband; and $|H(\omega_o + \omega_e)|$ is that obtained by the +1st sideband.

As can be seen from Eq. (10), when the RF signal ω_e is swept, by extracting the magnitudes of the $\omega_e - \Delta\omega$ and $\omega_e + \Delta\omega$ components, the magnitude response of the DUT in both sides of the optical carrier, i.e., $|H(\omega_o - \omega_e)|$ and $|H(\omega_o + \omega_e)|$, can be obtained. The component beat by the nth- and $(n \pm 1)$th-order sidebands will not introduce any measurement errors, because its frequency is ω_e, which does not contribute to the measurement results. In addition, the carrier suppression in the ODSB modulation is not necessary, since the optical carrier only contributes to the components with frequencies of $n\omega_e$ and $\Delta\omega$. These frequency components are not used in the proposed system. It should be noted that if ϕ is an invariable, i.e., the two branches have a fixed phase difference, the phase response of the DUT can also be achieved.

To verify the principle, a numerical simulation performed by OptiSystem is performed. The DUT is assumed to be an ideal FBG, which has a center wavelength of 1553.6 nm, a notch depth of 38 dB, and a bandwidth of 10 GHz. The RF source has a frequency sweeping

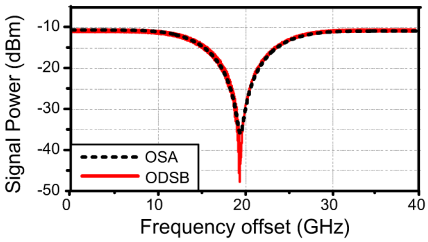

Fig. 2. Simulated magnitude responses by using the proposed method, and an OSA with a resolution of 0.02 nm.

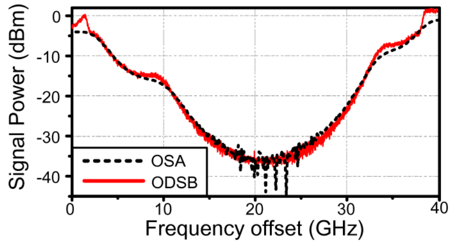

Fig. 3. Measured magnitude responses of an FBG, by the proposed method and the 0.02 nm OSA.

range of 0–20 GHz, and a scanning step of 10 MHz. The bandwidth of the PD is 40 GHz. Figure 2 shows the simulated magnitude response using the proposed system. As a comparison, the simulated magnitude response of the FBG, by an optical spectrum analyzer (OSA) with a resolution of 0.02 nm, is also plotted in Fig. 2. As can be seen, the two curves agree well, except for the deep notch. The proposed approach can obtain the 38 dB notch depth, while that achieved by the OSA is only about 25 dB, indicating that the ODSB-based method has a higher measurement resolution.

A proof-of-concept experiment, based on the setup shown in Fig. 1(a), is also carried out. A light wave, with a power of 16 dBm, from a tunable laser source (Agilent N7714A), is divided into two branches, by a 50:50 optical coupler. One portion is modulated by a RF signal at an MZM. The MZM has a 3 dB bandwidth of 30 GHz, and a half-wave voltage of 5 V at 1 GHz (Fujitsu). The RF signal is generated by a microwave signal generator (Agilent E8267D). The frequency sweeping range of the RF signal is 20 GHz, and the sweeping step is 10 MHz. An FBG is used as the DUT, which has a center wavelength of 1550.220 nm, a notch depth of 37 dB, and a 3 dB bandwidth of 20.3 GHz. The other part of the optical signal passes through an acousto-optic modulator, to have its frequency shifted by a fixed 55 MHz. A 50 GHz PD (u^2t), with responsivity of 0.65 A/W, is employed to perform the optical to electrical conversion. The generated electrical signal is then received by an ESA (Agilent 9030A). The microwave signal generator, and the electoral spectrum analyzer, are connected to a computer via GPIB cables. A LabVIEW program is used to control the two instruments, and acquire, process, and store data from the ESA. As a reference, the magnitude response of the FBG is also measured by an OSA (YOKOGAWA AQ637C), with a resolution of 0.02 nm.

Figure 3 shows the magnitude responses of the FBG, measured by the proposed system and the OSA, in a frequency range of 40 GHz. The two curves agree well. The small deviation in the edge is possibly due to the frequency-dependent power variation of the microwave signal generator, or the uneven frequency response of the microwave components used in the system, which can be minimized by accurate calibration of the measurement system. Due to the relatively slow communication between the LabVIEW program and the two instruments, the measurement of the magnitude responses of the FBG costs about 20 min. During this period, the frequency response of the FBG may have evident drift in the laboratory environment, which would also introduce considerable measurement error. If the measurement time can be reduced, the measurement should be more accurate. It should be noted that the resolution of the measurement is limited mainly by the tuning resolution of the microwave signal generator, the resolution bandwidth (RBW) of the ESA, and the linewidth of the laser source, which can be much less than 1 MHz.

In conclusion, a novel approach to perform an optical magnitude response measurement, using optical double-sideband (ODSB) modulation, was proposed and experimentally demonstrated. The magnitude response of an FBG in the range of 40 GHz was measured, with a resolution of 10 MHz, by using a 20 GHz microwave signal source. The proposed method is simple, wideband, and efficient, which can be applied in high-resolution optical device characterization.

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