Hyperfine Magnitude Response Measurement for Optical Filters based on Low-frequency Detection

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***Abstract*—An electrical method for characterizing optical filters is proposed and demonstrated based on low-frequency detection, which enables magnitude frequency response measurement with hyperfine resolution up to 50 kHz and doubled measuring frequency range in the electrical domain.**

I. Introduction

High-resolution measurement of the magnitude response of optical filters is critical to understand the fine spectral structure of optical filters and realize hyperfine microwave signal processing in the optical domain [1]. Conventionally, the amplified spontaneous emission (ASE) method [2] is used, but it is limited frequency resolution (~1GHz) by the resolution of commercial grating-based optical spectrum analyzers (OSA). The phase-shift approach [3,4] and the interferometry method [5,6] rely on a wavelength scan of a tunable laser source, which require extremely stable and fast tunable optical sources, if high-resolution is involved. The swept frequency methods enable very high resolution measurement with the help of the developed electrical domain techniques [7-13]. However, the optical single-sideband (OSSB) technique [7-11] requires complex microwave modulation and suffers from the residual harmonic sidebands due to the modulation nonlinearity. The optical double-sideband (ODSB) technique [12-13] features doubled measurement range and immunity to modulation nonlinearity. Nevertheless, this method needs a wideband photodetector (PD) and electrical spectrum analyzer (ESA) as a receiver, and requires fast alignment of central frequency between the microwave source and the receiver at every swept frequency point.

In this paper, we propose and demonstrate, for the first time to our knowledge, a hyperfine magnitude response measurement of optical filters based on low-frequency detection. As is shown in Fig. 1, the proposed method consists of two phase modulators (PM1 and PM2) and an acoustooptic frequency shifter (FS) together with the optical filter under test (FUT) located in a heterodyne interferometer (HI). The optical carriers of two PMs are originated from the same source but frequency detuned with respect to each other through the FS. The modulation sidebands of PM1 pass through the FUT and heterodyne with those of PM2, which allows extracting the magnitude response of FUT from two fixed-frequency heterodyne components in the low-frequency regime, by carefully choosing the two microwave driving frequencies. Our method features not only the immunity to the undesired spurious sidebands, but also the bidirectional frequency sweeping with doubled measuring frequency range. Moreover, it allows hyperfine magnitude response measurement for optical band-pass or band-stop filters with low-speed PD and ESA in the electrical domain.

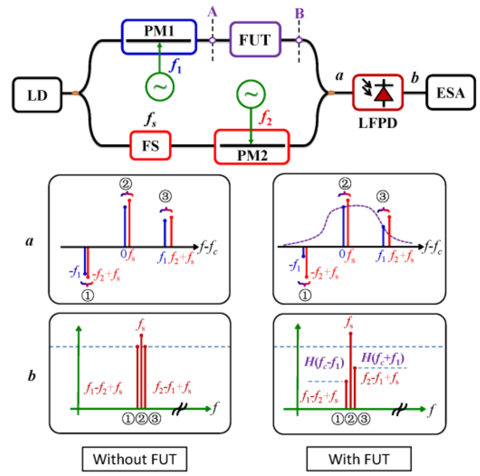

Fig. 1. Schematic diagram of the proposed optical filter measurement.

II. Operating Principle

As shown in Fig. 1, an optical carrier at angular frequency ω_c in the upper branch of HI is modulated in the PM1 at the microwave frequency ω_1. The same carrier in the lower branch of HI is frequency shifted by ω_s in the FS and then modulated in the PM2 at the microwave frequency ω_2. The combined optical signals of HI are detected by a PD, given by [14-15]

$$i = R\left| e^{j\omega_c t}\left[\begin{array}{l} \sum_{k=-\infty}^{+\infty} J_k(m_1) H(\omega_c + k\omega_1) e^{j(\omega_c + k\omega_1)t} \\ +\eta e^{j\psi} \sum_{q=-\infty}^{+\infty} J_q(m_2) e^{j(\omega_c + \omega_s + q\omega_2)t} \end{array} \right] \right|^2 \quad (1)$$

with the magnitude response $H(\omega)$ of FUT, the modulation depths m_i (i=1,2) of PM1 and PM2, the responsivity R of PD, and the relative amplitude η and phase ψ between the two branches of HI, respectively. From Eq. (1), the heterodyne spectrum can be quantified with the Jacobi-Anger expansion as

$$i_f(q\omega_2 - k\omega_1 \pm \omega_s) = 2\eta J_q(m_1) J_k(m_2) H(\omega_c \pm k\omega_1) R(q\omega_2 - k\omega_1 \pm \omega_s) \quad (2)$$

The reference measurement can be obtained through bypassing the FUT (A directly connects to B), as given by

$$i_r\left(q\omega_2 - k\omega_1 \pm \omega_s\right) = 2\eta J_q\left(m_1\right) J_k\left(m_2\right) R\left(q\omega_2 - k\omega_1 \pm \omega_s\right) \quad (3)$$

For a low-frequency detection, the frequency difference between two microwave frequencies ω_1 and ω_2 is set very small and fixed ($k\omega_2$-$q\omega_1$=$\Delta\omega$>0), the magnitude frequency response $H(\omega_c \pm k\omega_1)$ of FUT can be determined by

$$H\left(\omega_c \pm k\omega_1\right) = i_f\left(q\omega_2\text{-}k\omega_1 \pm \omega_s\right) / i_r\left(q\omega_2\text{-}k\omega_1 \pm \omega_s\right) \quad (4)$$

It is obvious that the magnitude frequency response of FUT can be determined from the two frequency-fixed low-frequency components of heterodyne signal.

III. Experiment and Results

In the experiment, the optical carrier from a laser diode with a line-width of 50 kHz at λ_c=1550.362 nm is modulated in the PM1 and sent to the FUT (λ/4 phase-shifted FBG) in the upper branch of HI. The same optical carrier is frequency-detuned by 70 MHz in the FS and modulated in the PM2 in the lower branch. The combined optical signal is collected and analyzed by a low-speed PD (with a bandwidth of 1 GHz) and ESA. The two MS and ESA are connected to a computer and controlled by a MATLAB program via NI-VISA protocols.

Figure 2 shows typical heterodyne electrical spectra in the case of f_1=16 GHz and f_2=16.0005 GHz, the desired low-frequency components are measured to be -71.14 dBm at 69.5 MHz (f_2-f_1-f_s) and -57.42 dBm at 70.5 MHz (f_2-f_1+f_s), respectively, with the FUT inserted. Meanwhile, the desired components are -48.21 dBm at 69.5 MHz (f_2-f_1-f_s) and -48.36 dBm at 70.5 MHz (f_2-f_1+f_s), respectively, with the FUT bypassed. Therefore, the magnitude frequency response of FUT are determined to be $H(f_c$-$f_1)$=-22.93 dB and $H(f_c$+$f_1)$=-9.06 dB at the offset frequency f_1=16 GHz with respect to the central wavelength of 1550.362 nm.

The heterodyne spectra show extremely narrow spectrum lines due to the inherent coherence among the heterodyne optical signals originating from the same optical carrier. The measurement can be easily swept to other frequencies f_1 by simply setting the microwave frequencies as f_2= f_1+0.5 MHz. As shown in Fig.3, the measured magnitude response of FUT agree with the results with the conventional ASE method, verifying our electrical measurement. Further, we demonstrate a detail measurement with the swept frequency step of 1 MHz, 500 kHz and 50 kHz in the inset of Fig.3, indicating the repeatable measurement with hyperfine resolution. Besides, the specifically chosen FUT demonstrates that our method is applicable for both band-pass and band-stop optical filters.

IV. Conclusion

We have proposed and demonstrated an electrical method with a resolution up to 50 kHz for characterizing magnitude frequency response of optical filters based on low-frequency detection. Compared to the traditional ODSB technique, our method enables high-resolution and wide frequency range measurement of optical filters with low-speed PD and ESA. Moreover, it only needs to receive and analyze low-frequency signals at fixed frequencies, which largely speeds up the swept frequency measurement. Our scheme works without any small-signal assumption, and it is applicable for different driving levels and operating wavelengths as long as the required frequency relationship is satisfied, in the meantime, it is robust to path impairments, thermal fluctuations and mechanical vibrations due to the heterodyne mode of HI. Note that the measurement resolution is limited mainly by the tuning resolution of the microwave generator, the resolution bandwidth (RBW) of the ESA, and the line-width of the laser source [13], which can be better than 50 kHz if with a narrower line-width laser source.

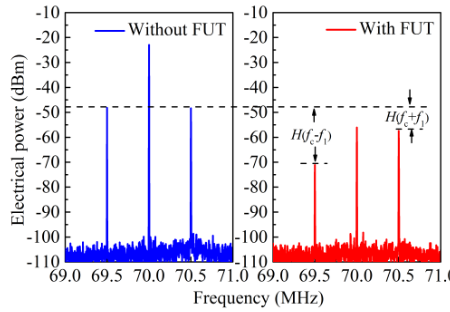

Fig. 2. Typical heterodyne spectrum in the low-frequency regime.

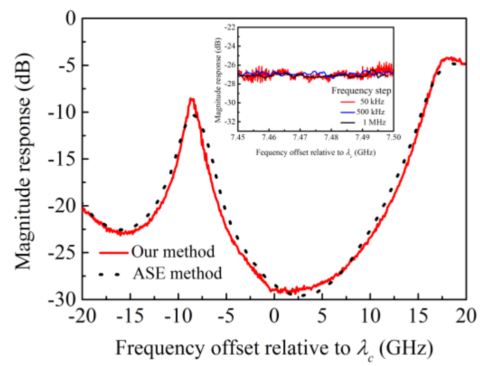

Fig. 3. Measured magnitude responses of FUT.

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