Ultrahigh-Resolution Optical Vector Analysis for Arbitrary Responses Using Low-Frequency Detection

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***Abstract*— We propose and experimentally demonstrate an ultrahigh-resolution optical vector analyzer (OVA) for arbitrary responses measurement by using microwave photonic frequency down-conversion and fixed low-frequency detection. It avoids high-speed photodetection and ultrawideband electrical phase-magnitude detection, which are the key challenges to the previous OVAs based on microwave photonics (MWPs). Additionally, the proposed OVA has the capability of measuring arbitrary spectral responses. A high-resolution optical frequency-swept signal generated by using MWP-based techniques is separated into two parts. One portion propagates through an optical device under test (DUT) and then directs to a photodetector (PD), which carries out the spectral responses. In the other branch, the optical signal is accurately shifted by a small frequency and then sent to the PD. By square-law detection, the spectral responses of the optical DUT are thus transferred to a low-frequency photocurrent with a frequency equaling to the shifted frequency. Thus, the spectral responses can be obtained by detecting the photocurrent using a low-frequency electrical phase-magnitude detector working at a fixed frequency. In the experiment, a measurement system is established, by which the magnitude and phase responses of optical devices, such as an optical Hilbert transformer and an optical bandpass filter, are successfully measured. The measurement results are verified by the previous MWP-based OVAs and a commercial instrument.**

***Index Terms*— Microwave photonics, measurement techniques, electrooptic modulators, optical variables measurement, phase detection.**

I. Introduction

ACCURATE measurement of the spectral responses of optical devices and components that can finely handle optical spectrum is essential for their development, fabrication and application [1]–[3]. The frequency resolution of the state-of-the-art programmable optical filter is as high as several MHz [1], and the bandwidth of the high-fineness optical devices is as narrow as sub-MHz. For example, a high-Q optical resonator, having a bandwidth of 97 kHz, is now available [2]. To accurately observe the spectral responses of these high-performance devices and components, optical vector analyzers (OVAs) using microwave photonics (MWP) based techniques were developed [4]–[12], which can be grouped into two categories, namely, OVAs using optical channel estimation (OCE) techniques and OVAs adopting electrical frequency sweeping. The OCE-based OVAs achieve the spectral responses by extracting the spectral changes of an optical orthogonal frequency-division multiplexing (OFDM) signal after going through an optical device [4], [5]. It features one-shot measurement but usually has a small dynamic range owing to the limited maximum input electrical power. Additionally, the nonlinear optical device cannot be accurately measured by the OCE-based method, as the spectrum of the OFDM signal would be changed by both the linear spectral responses and the nonlinearity.

In contrast, the OVAs based on electrical frequency sweeping measure the spectral responses at a series of discrete frequencies by employing electrical frequency sweeping via electrical-to-optical conversion, generally, optical single-sideband (OSSB) or optical double-sideband (ODSB) electro-optic modulation. This kind of method has an attractive ultrahigh resolution, by which a resolution of sub-Hz is theoretically achievable [6] and a resolution of 78 kHz is experimentally realized [7]. To improve the performance of the OVAs based on electrical frequency sweeping, numerous approaches have been developed to extend the measurement range, enlarge the dynamic range, reduce the measurement errors, etc. However, ultrawideband detection (e.g., from several kHz to 67 GHz), which is achieved by high-speed photodetectors and ultrawideband electrical phase-magnitude detectors, is essential to obtain the spectral responses in a broad frequency range, which is complex and costly. Recently, to achieve low-frequency detection, an OVA employing two sets of MWP-based laser sources was proposed [13], but it demands that the two optical signals from the two laser sources have a fixed low-frequency spacing and are coherent. Although the photodetection and the spectral responses extraction are greatly simplified, the optical sources to generate the testing optical signal are complicated.

In this letter, an ultrahigh-resolution OVA for arbitrary response measurement using fixed low-frequency detection is proposed and constructed. It features simple configuration and low cost, as the frequency-shifted signal is simply achieved

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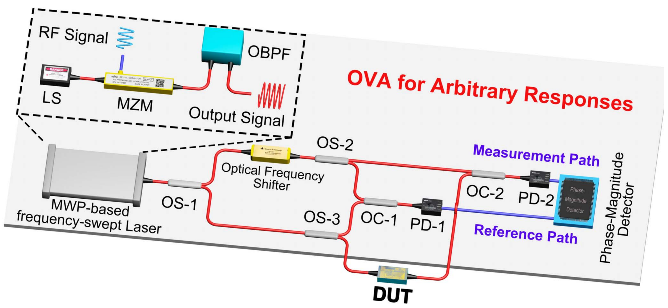

Fig. 1. The configuration of the proposed OVA for arbitrary response measurement. LS, laser source; OBPF, optical bandpass filter; MZM, Mach-Zehnder modulator; OS, optical splitter; DUT, device under test; OC, optical coupler; PD, photodetector.

by an optical frequency shifter and a fixed low-frequency detector is used to achieve the spectral responses. In addition, the proposed OVA can accurately obtain arbitrary responses due to the two separated optical signals. In the experiment, a measurement system is established, by which an optical Hilbert transformer, as well as an optical bandpass filter, are characterized, which demonstrates the capability of the arbitrary spectral response measurement. The measurement results are verified by a conventional OSSB-based OVA and an optical spectrum analyzer equipped with the option for optical component analysis.

II. Principle

Figure 1 demonstrates the configuration of the proposed OVA for measuring arbitrary responses, which is achieved by optical frequency shifting and fixed low-frequency detection. An ultrahigh-resolution frequency-swept laser source, which is achieved by MWP-based techniques [14]–[16], produces a frequency-swept optical signal. The optical field is generally expressed as

$$E_{in}(t) = A\left(f_e\right)\exp\left[i\left(f_o + f_e\right)t + i\varphi\left(f_e\right)\right] \tag{1}$$

where f_o and f_e denote the frequencies of the optical signal from the laser source and the frequency-swept RF signal, respectively. $A(f)$ and $\varphi(f)$ present the amplitude and the phase at different RF frequencies.

Splitting the frequency-swept optical signal into two parts. One is shifted by an optical frequency shifter with a fixed small frequency (i.e., Δf), as shown in the upper branch. The other portion, in the lower branch, carries the spectral responses when propagating through an optical device under test (DUT). The two optical signals are respectively given by

$$E_{up}(t) = A_{up}\left(f_e\right)\exp\left[i\left(f_o + f_e - \Delta f\right)t + i\varphi_{up}\left(f_e\right)\right] \tag{2}$$

$$E_{low}(t) = A_{low}\left(f_e\right)H\left(f_o + f_e\right)\exp\left[i\left(f_o + f_e\right)t + i\varphi_{low}\left(f_e\right)\right] \tag{3}$$

where $A_{up}(f)$, $A_{low}(f)$, $\varphi_{up}(f)$ and $\varphi_{low}(f)$ are the amplitudes and phases of the transmitted optical signals in the upper and lower branches. $H(f)$ is the transmission function of the optical DUT.

By coupling and photodetecting the two optical signals using a low-speed photodetector (PD), a photocurrent with an angular frequency of Δf is generated, which is

$$\begin{aligned} i(t) &= \eta\left[E_{up}(t) + E_{low}(t)\right]\left[E_{up}(t) + E_{low}(t)\right]^* \\ &= \eta A_{low}\left(f_e\right)A_{up}\left(f_e\right)H\left(f_o + f_e\right) \\ &\quad \times \exp\left\{i2\pi\Delta f t + i\left[\varphi_{low}\left(f_e\right) - \varphi_{up}\left(f_e\right)\right]\right\} \end{aligned} \tag{4}$$

where η is the responsivity of the low-speed PD at Δf. Then, using a low-frequency electrical phase-magnitude detector working on a fixed frequency of Δf, the information of the magnitude and phase is acquired. The expression of the photocurrent in the frequency domain can be written as

$$\begin{aligned} i\left(\Delta f, f_o + f_e\right) &= \eta A_{low}\left(f_e\right)A_{up}\left(f_e\right)H\left(f_o + f_e\right) \\ &\quad \times \exp\left\{i\left[\varphi_{low}\left(f_e\right) - \varphi_{up}\left(f_e\right)\right]\right\} \end{aligned} \tag{5}$$

A calibration step to de-embedding the transmission function of the system is performed by directly connecting the two test ports, where $H(\omega)$ =1. Thereby, the photocurrent in the calibration processing is

$$\begin{aligned} i_{cal}\left(\Delta f, f_o + f_e\right) &= \eta A_{low}\left(f_e\right)A_{up}\left(f_e\right) \\ &\quad \times \exp\left\{i\left[\varphi_{low}\left(f_e\right) - \varphi_{up}\left(f_e\right)\right]\right\} \end{aligned} \tag{6}$$

From (5) and (6), the transmission function of the DUT can be calculated, which is

$$H\left(f_o + f_e\right) = \frac{i\left(\Delta f, f_o + f_e\right)}{i_{cal}\left(\Delta f, f_o + f_e\right)} \tag{7}$$

As can be seen from (7), the transmission function of the optical DUT can be achieved by detecting the low-frequency photocurrent with a fixed frequency of Δf at a series of the RF frequencies. Thus, the proposed OVA can be achieved by low-speed photodetectors and fixed low-frequency electrical phase-magnitude detectors.

III. Experiment and Discussion

An OVA for arbitrary response measurement adopting the configuration shown in Fig. 1 is experimentally established. The key component is an optical frequency-swept laser source, which is comprised of a narrow-linewidth laser source (LS), a high-speed Mach-Zehnder modulator (MZM) and an optical bandpass filter. A tunable laser source (TLS, TeraXion PS-TNL) produces a 1549.75-nm continuous-wave (CW). A vector network analyzer (VNA, R&S ZVA67), which is equipped with the mixer measurement option, provides a frequency-swept RF signal. Then, a high-speed MZM (Fujitsu) biased at minimum transmission point (MITP) is employed to achieve electro-optic modulation. By filtering out one first-order sideband using a tunable optical bandpass filter (Yenista XTM-50), a frequency-swept laser source with ultrahigh resolution is thus generated. An acoustic-optical modulator (AOM, Gooch & Housego) is used as an optical frequency shifter, which accurately introduces 80-MHz frequency shift. A programmable optical filter (Finisar WaveShaper 16000s), which respectively has optical Hilbert transform or optical bandpass responses by uploading the predesigned configurations, is used as an optical DUT. Two low-speed PDs (ThorLabs PDB45C-AC) is inserted to achieve optical-to-electrical conversion. The phase-magnitude detector working

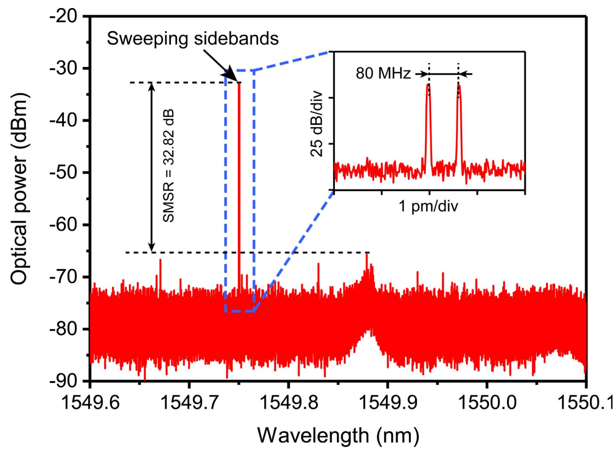

Fig. 2. The optical spectrum of the two-tone optical signal in the reference path obtained by the high-resolution OSA.

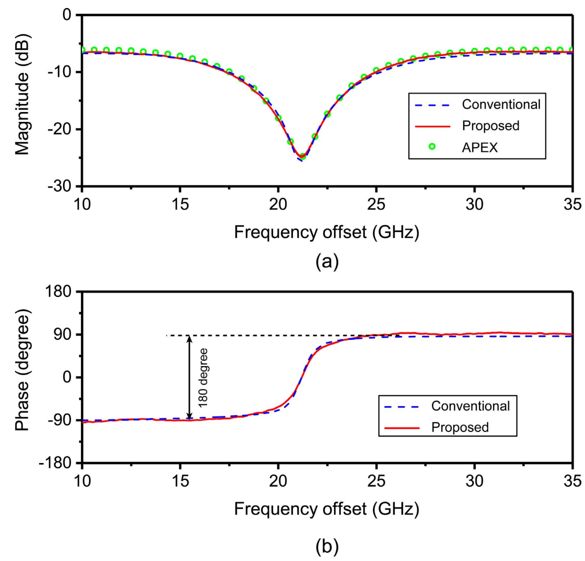

Fig. 3. Spectral responses of the configured optical Hilbert transformer measured by the proposed OVA, the conventional OSSB-based OVA and the high-resolution OSA. (a) Magnitude responses and (b) phase responses.

at 80 MHz in the VNA is employed to detect the magnitude and phase differences between the photocurrents in the measurement and reference paths. By sweeping the frequency, the magnitude and phase responses can be obtained by the VNA with the mixer measurement option. It should be noted that the resolution as high as 1 kHz is available for the experimentally constructed OVA owing to the 1-kHz linewidth of the TLS and the ultrahigh-resolution electrical frequency sweeping. Theoretically, sub-Hz resolution is achievable if a sub-Hz-linewidth laser is used [17]. A high-resolution optical spectrum analyzer (OSA, APEX AP2040C) is adopted to monitor the optical spectra.

Figure 2 shows the optical spectrum of the two-tone optical signal comprised of the original and frequency-shifted signals in the reference path, when the frequency of the RF signal from the VNA is set to 10 GHz. It can be seen from the measured optical spectrum that the side-mode suppression ratio (SMSR) is about 32.82 dB. It indicates that the power of the desired component generated by the two dominant modes is 65.64-dB higher than those of the undesired components produced by the side modes. Thus, high accuracy and large dynamic range are achievable for the proposed OVA. As the AOM induces an 80-MHz frequency shift, the frequency spacing between the two tones is 80 MHz, as shown the inset in Fig. 2.

Figure 3 shows the spectral responses of the optical Hilbert transformer, which are measured using three different methods, such as the proposed OVA, the conventional OSSB-based OVA and the high-resolution OSA. The spectral responses of the configured optical Hilbert transformer are accurately obtained by the proposed OVA with a resolution of 5 MHz (red solid lines). It can be seen from Fig. 3(b), the phase reverses around 21 GHz offset the optical carrier, and the phase is shifted by about 180 degrees. When reversing the phase, insertion loss (IL) accordingly appears, which demonstrates a notch in the measured magnitude response, as shown in Fig. 3(a). To verify the measurement results, the spectral responses obtained by the OSSB-based OVA (blue dashed lines) and the APEX method achieved by high-resolution OSA (green circles) are also plotted. Since the APEX method measures the frequency responses by detecting the optical powers before and after the optical device under test (DUT), only the magnitude response can be achieved. The comparison shows that the obtained magnitude responses measured, as shown in Fig. 3(a), are coincident. The phase responses observed by the proposed OVA is coincident with that characterized by the conventional OSSB-based OVA, as shown in Fig. 3(b). Hence, the validity of the spectral responses obtained by the proposed OVA is confirmed.

It is worth to mention that slight fluctuation can be observed in the phase response observed by the proposed OVA. It is because the original and the frequency-shifted optical signals are transmitted to the PD via two separated optical paths, in the phase relationship between the two optical signal is sensitive to the environmental perturbation. By carefully controlling the temperature and shortening measurement time, the fluctuation can be suppressed and the accurate measurement results are achievable.

Since only the original frequency-swept optical signal goes through the optical DUT while the frequency-shifted optical signal is directly transmitted to the PD, the proposes OVA inherently has the ability to measure the arbitrary responses. Figure 4 demonstrates the spectral responses of an optical bandpass filter, which are characterized by the proposed OVA and the high-resolution OSA. By employing the proposed OVA, the spectral responses from 10 GHz to 50 GHz offsetting the optical carrier are observed (red lines). Considering that the OSSB- and ODSB-based OVAs are unable to achieve bandpass response as the optical carrier is always located in the stopband and would be greatly suppressed, the bandpass magnitude response acquired by the high-resolution OSA is plotted in Fig. 4(a) for comparison (blue line). It can be seen from Fig. 4(a) that the two measured magnitude responses are consistent with each other. It demonstrates the capability for the arbitrary response measurement. It is worth to mention that, restricted by the spectral noise of the low-frequency PDs

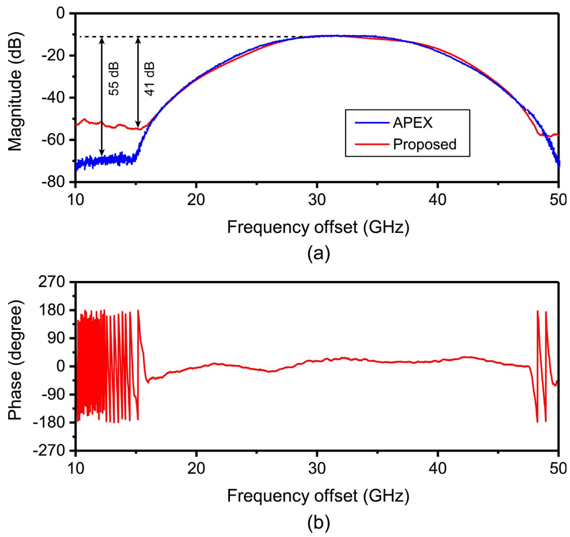

Fig. 4. Spectral responses of the configured optical bandpass filter measured by the proposed OVA and a commercial instrument. (a) Magnitude responses and (b) phase response.

and the sensitivity of the VNA, the measurable IL for the experimentally implemented OVA is about 50 dB, as shown in Fig. 4(a). Therefore, the dynamic range of 80 dB is achievable by taking into account the measurable gain of 30 dB.

IV. Conclusion

In conclusion, an ultrahigh-resolution OVA achieved by fixed low-frequency detection for measuring the arbitrary spectral responses is proposed and experimentally established. Benefitting from the accurate optical frequency shift, the spectral responses are transferred to a fixed low-frequency photocurrent. Hence, the ultrawideband detection, which is the critical challenge to the previous OVAs based on electrical frequency sweeping, is avoided. Additionally, the proposed OVA can accurately measure arbitrary spectral responses. The proposed method is experimentally implemented to characterize an optical programmable filter configured to realize an optical Hilbert transformer or optical bandpass filter. The measurement results agree with those measured by the OSSB-based OVA and the high-resolution OSA. It is worth to mention that, limited by the bandwidth of the electro-optic devices, the measurement range is generally about 40 GHz. By multichannel measurement and precise spectrum stitching based on the optical frequency comb (OFC) [18], the measurement range can be extended without deteriorating the resolution.

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