High-resolution optical vector network analyser employing optical double-sideband modulation and optical Hilbert transform

Min Xue, Wei Chen, Beibei Zhu and Shilong Pan✉

The authors propose and experimentally demonstrate an optical vector network analyser (OVNA) employing optical double-sideband modulation and optical Hilbert transform. The optical device-under-test is characterised with and without optical Hilbert transform. Then, by employing post signal processing, accurate spectral responses on upper and lower sides of the optical carrier are observed. A proof-of-concept experiment for measuring gain and absorption responses of the stimulated Brillouin scattering (SBS) is performed, showing that the proposed OVNA is able to accurately measure the gain and absorption responses of the SBS. The measurement error is smaller than 1%.

Introduction: In frontier researches and emerging applications, such as quantum optical storage [1] and high-resolution optical signal processing [2], optical devices being able to finely handle the optical spectrum are the key components. To develop and fabricate such optical devices, a high-resolution optical vector network analyser (OVNA) is an essential instrument, by which the characterisation of the spectral responses, including the magnitude and phase responses, is achievable. A promising method to implement high-resolution OVNAs is to employ optical single-sideband (OSSB) modulation [3–8], by which sub-Hz resolution is potentially available [3]. However, the sideband suppression ratios (SSRs) of the practical OSSB modulations are always limited. The residual unwanted first-order sideband would introduce significant measurement error, leading to a small measurement dynamic range. Besides, only one sideband is useful, so the spectral measurement range is relatively small. To achieve wideband and efficient measurement, OVNAs employing optical double-sideband (ODSB) modulation were proposed and implemented [9, 10]. The key challenge is to separate the spectral responses upper and lower the optical carrier from the measured responses, which results in that the configuration is complex and difficult to construct. In addition, complicated and challenging calibration processing, and broadband electrical frequency mixing are required.

In this Letter, an ODSB-based OVNA utilising an optical Hilbert transformer is proposed and developed, which measures the responses of the optical devices using the upper and lower sidebands. As compared with the previous OSSB- and ODSB-based OVNA, the expensive and complex configuration as well as the complicated calibration processing is avoided.

Fig. 1 demonstrates the configuration of the proposed ODSB-based OVNA utilising optical Hilbert transform. In the OVNA, a laser diode (LD) produces a lightwave with a frequency of f_o. Then, an electro-optic modulator (EOM) modulates an RF signal with a frequency of f_e on the optical carrier. An ODSB signal is thus generated. Mathematically, the ODSB signal can be written as

$$E_{in}(f) = E_{-1}\cdot\delta[f-(f_o-f_e)] + E_0\cdot\delta(f-f_o) + E_{+1}\cdot\delta[f-(f_o+f_e)] \quad (1)$$

where E_n is the complex amplitude, including the amplitude and initial phase, of the nth-order sideband.

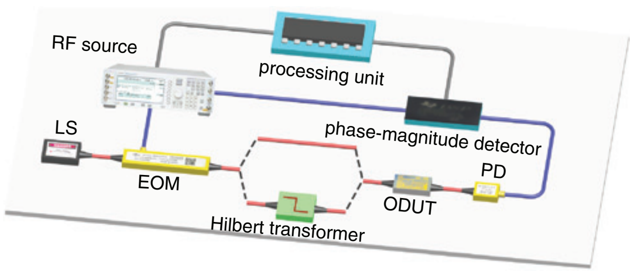

Fig. 1 *Configuration of the proposed ODSB-based OVNA utilising optical Hilbert transform. LS, laser source; EOM, electro-optic modulator; ODUT: optical device-under-test; PD, photodetector*

Then, two measurements are performed. In the first measurement, the ODSB signal directly propagates through an optical device-under-test (ODUT). The optical field of the propagated optical signal is

$$E_1(f) = E_{-1}H(f_o-f_e)\delta[f-(f_o-f_e)] + E_0H(f_o)\delta(f-f_o) + E_{+1}H(f_o+f_e)\delta[f-(f_o+f_e)] \quad (2)$$

where $H(f)$ is the transmission function of the ODUT.

By photodetecting, a photocurrent with frequency of f_e is generated, which is given by

$$i_1(f_e) = \eta E_0E_{-1}^*H(f_o)H^*(f_o-f_e) + \eta E_{+1}E_0^*H(f_o+f_e)H^*(f_o) \quad (3)$$

where η is the responsivity of the photodetector (PD).

In the second measurement, an optical Hilbert transformer is inserted before the ODUT to reverse the phase of one sideband of the ODSB signal from the EOM. The phase-reversed signal is

$$E_2(f) = E_{-1}H(f_o-f_e)\delta[f-(f_o-f_e)] + E_0H(f_o)\delta(f-f_o) - E_{+1}H(f_o+f_e)\delta[f-(f_o+f_e)] \quad (4)$$

Accordingly, the photocurrent is

$$i_2(f_e) = \eta E_0E_{-1}^*H(f_o)H^*(f_o-f_e) - \eta E_{+1}E_0^*H(f_o+f_e)H^*(f_o) \quad (5)$$

From (4) and (5), we can obtain the transmission functions upper and lower the optical carrier

$$i_1(f_e) + i_2(f_e) = 2\eta E_0E_{-1}^*H(f_o)H^*(f_o-f_e) \quad (6)$$

$$i_1(f_e) - i_2(f_e) = 2\eta E_{+1}E_0^*H(f_o+f_e)H^*(f_o) \quad (7)$$

A calibration process is performed to observe the transmission function of the measurement system, where the probe signals are directly sent to photodetector. In this case, $H(\omega) = 1$ and we have

$$i_{1-sys}(f_e) + i_{2-sys}(f_e) = 2\eta E_0E_{-1}^* \quad (8)$$

$$i_{1-sys}(f_e) - i_{2-sys}(f_e) = 2\eta E_{+1}E_0^* \quad (9)$$

From (6)–(9), the accurate responses of the ODUT upper and lower the optical carrier are acquired, which are

$$H(f_o+f_e) = \frac{i_1(f_e) - i_2(f_e)}{[i_{1-sys}(f_e) - i_{2-sys}(f_e)]H^*(f_o)} \quad (10)$$

$$H(f_o-f_e) = \frac{i_1^*(f_e) + i_2^*(f_e)}{[i_{1-sys}^*(f_e) + i_{2-sys}^*(f_e)]H^*(f_o)} \quad (11)$$

where $H(f_o)$ is a constant.

In a proof-of-concept experiment, an OVNA based on the configuration shown in Fig. 1 is implemented. A continuous-wave (CW) produced from a tunable laser source (TLS, Agilent N7714A) is used as an optical carrier. At a 40-Gbps Mach-Zehnder modulator (MZM, Fujitsu) the optical carrier is modulated by a frequency-swept RF signal output by a vector network analyser (VNA, R&S ZVA67). The optical Hilbert transformer is achieved by a programmable optical filter (Finisar WaveShaper 4000s). The ODUT is the stimulated Brillouin scattering (SBS) generated in a 6-km single mode fibre (SMF). A high-speed PD (U^2T XPDV2120R) with a 3-dB bandwidth of 43 GHz is used to achieve optical-to-electrical conversion. The VNA receives and extracts the magnitude and phase of the generated photocurrents.

Fig. 2 demonstrates the measured spectral responses of the SBS with and without the optical Hilbert transform with different pump powers. As can be seen from Figs. 2*a* and *c*, with the increase of the pump power, the gain of the gain response and the loss of the absorption response grow. Hence, the gain and loss of the associated responses are accordingly changed. The phase shift increases and the slope gets sharp with the pump power, shown in Figs. 2*b* and *d*. Fig. 3 shows the magnitude and phase responses of the gain and absorption with different pump powers. It can be seen from Figs. 3*a* and *b* that the gain and phase shift of the gain responses increase with the pump power. Similarly, the loss of the absorption response gets large along with the pump power and the phase shift increases accordingly, as shown in Figs. 3*c* and *d*. It is worth to mention that the Rayleigh backscattering and Brillouin backscattering consequentially appear [11], which results in a gain peak in the measured absorption response. The Rayleigh and Brillouin backscattering signals are generated, and their powers increase with the pump power. Thus, in the measurement, the optical signal received by the PD is the aliasing of the probe signal and the backscattering signals. Since the power of the Rayleigh backscattering signal is very small compared with the optical carrier even when the pump power is high, its influence on the measurement results is small enough to be ignored. Similarly, the Brillouin backscattering signal also has very little influence on the measured gain response, due to its very small power as compared to the SBS-amplified + 1st-order sideband. However, the power of the Brillouin backscattering signal is near or much higher than that of the SBS-attenuated −first-order sideband, which brings a gain response in the measured absorption responses. Thereby, with the increase of the pump power, the suppression of the notch grows and the gain increases, as shown in Fig. 3*c*.

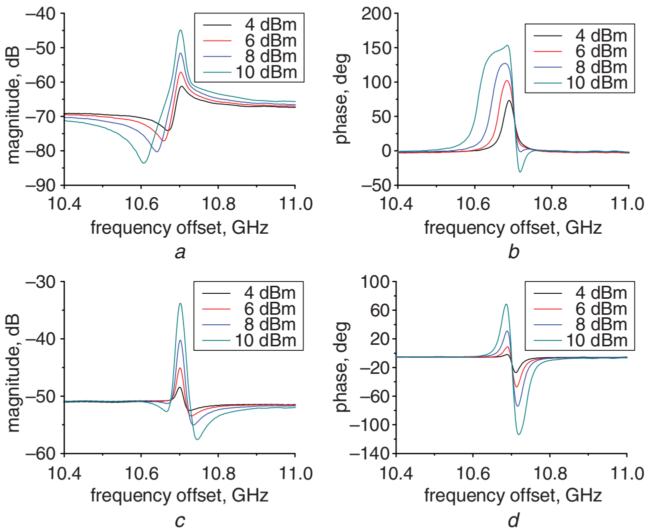

Fig. 2 *Measured responses with and without the optical Hilbert transform*

a Magnitude responses measured with optical Hilbert transform
b Phase responses measured with optical Hilbert transform
c Magnitude responses measured without optical Hilbert transform
d Phase responses measured without optical Hilbert transform

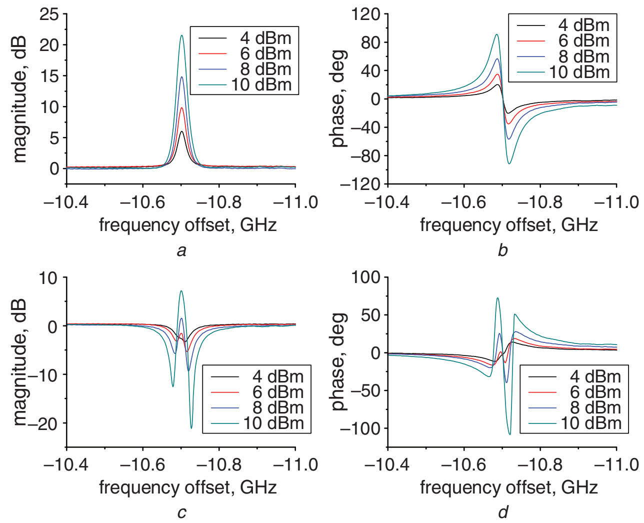

Fig. 3 *Obtained responses of the gain and absorption after post signal processing*

a Magnitude responses of the gain
b Phase responses of the gain
c Magnitude responses of the absorption
d Phase responses of the absorption

Theoretically, the spectral responses can be accurately obtained by the ideal phase reverse. However, the optical Hilbert transformer in the experiment is not ideal, leading to certain measurement errors. In the experiment, the photocurrent is cancelled by ~24 dB by using the Hilbert transformer, which indicates that the measurement error is smaller than 1%. By using a more accurate optical Hilbert transformer, the performance could be further improved.

Conclusion: A high-resolution OVNA adopting ODSB modulation and optical Hilbert transform was proposed and experimentally demonstrated. After processing the responses measured with and without Hilbert transform, the magnitude and phase responses of the gain and absorption of the SBS upper and lower optical carrier were experimentally characterised. The measurement error is smaller than 1%.

Acknowledgments: This work was supported in part by the National Key R&D Program of China (2017YFF0106900); National Natural Science Foundation of China (61705103, 61527820); Postgraduate Research and Practice Innovation Program of Jiangsu Province (KYLX16_0367); Fundamental Research Funds for the Central Universities (NC2018005).

Submitted: *6 May 2018* E-first: *6 February 2019*
doi: 10.1049/el.2018.5243
One or more of the Figures in this Letter are available in colour online.

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