Rayleigh speckles obtained from single mode fiber for wavelength measurement

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Abstract: We propose a novel wavemeter using Rayleigh speckle obtained by optical time domain reflectometry. It is experimentally demonstrated that the system can resolve multi-wavelength signal with 6 fm wavelength resolution and 25 nm bandwidth.

1. Introduction

Accurate wavelength measurement of light source is of vital importance to scientific researches and industrial applications. Conventional spectrometers use gratings for spectrum measurement [1]. In order to achieve higher spectral resolution, devices with large sizes to increase the optical path length between the grating and the detectors are used. Researchers have developed many types of spectrometers without using grating, such as disordered photonic crystals [2], multi-mode fiber based spectrometer [3] and integrating sphere based wavemeter [4], to minimize the size of spectrometer and improve the spectral resolution. The measurement bandwidth of multi-mode fiber based spectrometer is limited by the number of transmission modes. All these spectrometers use a camera to detect the speckle, which makes systems expensive, and introduces space insertion loss and also limits the measurement speed due to finite camera frame rate. The need of accurate spatial calibration of the individual components makes these spectrometers susceptible to environmental influence.

In this paper, we propose a novel all-fiber wavemeter using Rayleigh speckle obtained from standard single-mode fiber by optical time domain reflectometry (OTDR). After a pulsed lightwave is launched into a single-mode fiber, Rayleigh scattered lightwave is produced along the whole fiber. Rayleigh speckle with a jagged appearance is generated by the interference between Rayleigh backscattered lightwave from different reflection points within a pulse [5]. The characteristics of Rayleigh speckle varying with wavelength are used for wavelength determination. We achieve a wavelength resolution of 6 fm at 2 μs pulse width and experimentally demonstrate that the system has a 25 nm measurement bandwidth. The inverse relationship between pulse width and resolution, and the capability of the proposed system to distinguish multi-wavelength lightwave are also validated. Rayleigh speckle based wavmeter with high-resolution and broad bandwidth has the advantages of all-fiber, cost-effectiveness, compactness and lightweight.

2. Operation Principle

The experimental setup is illustrated in Fig.1(a). An acousto-optic modulator (AOM) is used to generate a probe pulse from light under test (LUT) for OTDR. Pulsed lightwave is launched into a 2 km single-mode fiber which is placed in a stable box to eliminate environmental perturbation. Rayleigh backscattered lightwave is received by photodetector (PD) via a circulator. Generally, a one-dimensional discrete model is adopted to analyze Rayleigh backscattering lightwave in fiber. The interval between Rayleigh scatter points is close to the scale of the lightwave wavelength [6]. The Rayleigh backscattering lightwave at position z_a of fiber can be written as

$$E_a = \sum_{m=a}^{a+N} A_{\mathrm{m}} exp\left\{ j2\pi ft - j\int_0^{z_m} \frac{2\pi n(z)}{\lambda} dz + j\varphi_0 \right\} \tag{1}$$

where $A_m = A\exp(-\alpha z_m)$, f is the optical frequency, λ is the optical wavelength, ϕ_0 is the initial phase of lightwave, c is the lightwave velocity in vacuum, $n(z)$ stands for non-uniform effective index distributed along the fiber and α is fiber attenuation coefficient. In Eq.(1), N roughly equals to the number of scatter points in fiber to be $N \approx P_w v/\lambda$, where P_w is the pulse width, v is lightwave velocity in the fiber [6]. Therefore, the intensity of Rayleigh speckle detected by PD can be expressed as

$$I_a \propto 2\sum_{m=a}^{a+N-1}\sum_{n=a}^{a+N-1} A_m A_n \exp(j\tfrac{2\pi}{\lambda}\textstyle\int_{-z_n}^{z_m} n(z)dz) \tag{2}$$

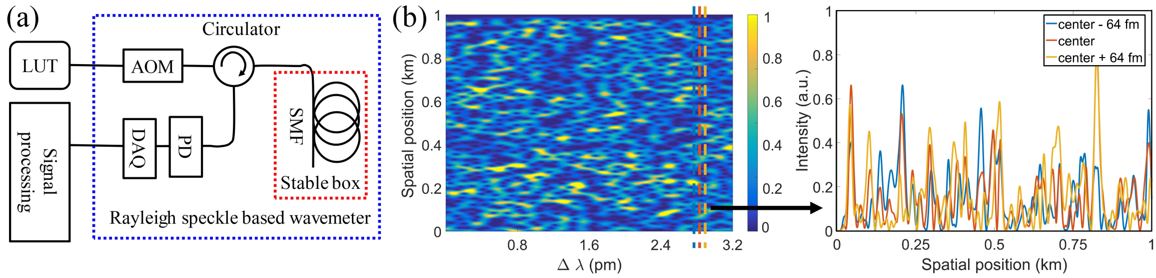

Fig. 1. (a) Experimental setup of Rayleigh speckle based wavemeter. LUT, lightwave under test; AOM, acousto-optic modulator; PD, photodetector; DAQ, data acquisition; SMF, single mode fiber. (b) Simulated Rayleigh speckles at different wavelengths for pulse of 200 ns width.

Eq.(2) reveals that there exist a one-to-one mapping relation between the wavelength of LUT and the intensity distribution of Rayleigh speckle. Fig.1(b) shows the simulated Rayleigh speckle as a function of wavelength. The simulation bandwidth is 3.2 pm with a step of 1.6 fm for 200 ns pulse width. From Fig.1(b), the selected three Rayleigh speckles at different wavelengths are obvious different.

Correlation coefficient is introduced to determine the wavelength resolution by analysing the similarity of Rayleigh speckles with different wavelengths. It can be considered that the two Rayleigh speckles are different with a correlation coefficient lower than 0.5. From Eq.(2), pulse width would influence the intensity distribution of Rayleigh speckle. To investigate the influence of pulse width, pulses with different widths are generated by controlling the driving signals to AOM and the results are shown in Fig.2. Fig.2(b) shows that the wavelength resolution scale inversely with the pulse width. More Rayleigh scatter points contribute for the intensity of Rayleigh speckle at a wider pulse, which makes the difference between Rayleigh speckles of adjacent wavelengths more obvious. The wavelength resolution achieve 6 fm with a 2 μs pulse width.

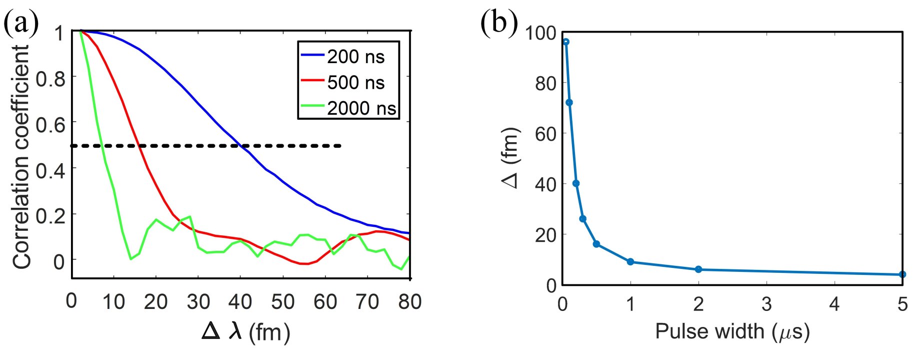

Fig. 2. (a) Correlation coefficient as a function of $\Delta\,\lambda$ with different pulse widths. Black dotted line corresponds to the correlation coefficient of 0.5. (b) The wavelength resolution as a function of pulse width.

Before using Rayleigh speckle based wavemeter for wavelength determination, a database D containing various Rayleigh speckles of different single-wavelength lightwave need to be acquired to build transmission matrix. Rayleigh speckle can also be regarded as a product of random media, and the relation between spatial intensity distribution I of Rayleigh speckle with unknown spectrum S and D for demodulation can be written as

$$\begin{pmatrix} D_{11} & \cdots & D_{m1} \\ \vdots & \ddots & \vdots \\ D_{1n} & \cdots & D_{mn} \end{pmatrix} \begin{bmatrix} S_1 \\ \vdots \\ S_m \end{bmatrix} = \begin{bmatrix} I_1 \\ \vdots \\ I_m \end{bmatrix} \tag{3}$$

where $D_{mn} = a_{mn}/S_{dm}$, with a_{mn} stands for the intensity of the mth single-wavelength lightwave at the nth point of Rayleigh speckle, and S_{dm} is the wavelength intensity of mth single-wavelength lightwave in the database. After determining D, the spectrum of LUT can be obtained by

$$S = D^{-1}I \tag{4}$$

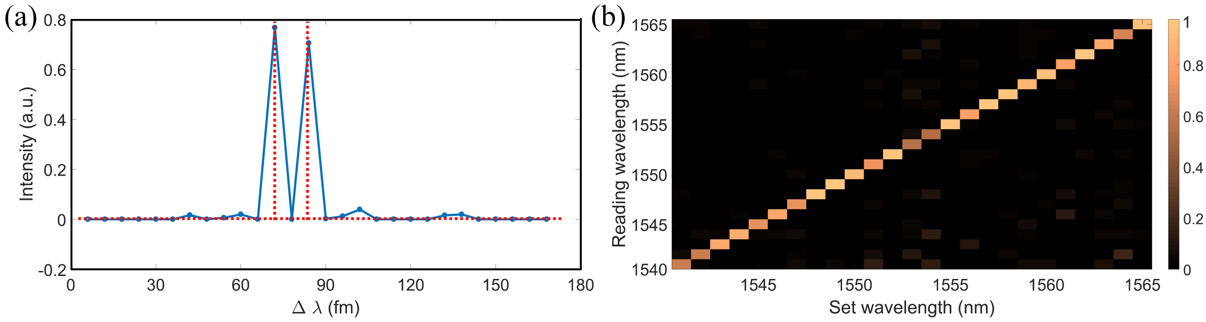

Fig. 3. Experimental results. (a) Reconstructed spectrum performed in the experiment. Red dotted line: real spectrum. Blue solid line: reconstructed spectrum. The center wavelength is 1550 nm. (b) Measured wavelength across the operational range of 1540 nm to 1565 nm with 1 nm interval.

3. Measurement results

Wavemeter based on Rayleigh speckle also has the capability to distinguish multi-wavelength lightwave. After applying a low-pass filter to obtained signal, the Rayleigh speckle of multi-wavelength lightwave is a summation of Rayleigh speckles of single-wavelength lightwave. Therefore, using transmission matrix method mentioned above can resolve the spectrum of multi-wavelength lightwave. The pulse width is set as 2 μs to make the wavemeter have 6 fm wavelength resolution. A lightwave with two wavelengths (the interval between two wavelengths is 12 fm) is injected into the Rayleigh speckle based wavemeter and the reconstructed spectrum calculated by Eq.(4) is shown in Fig.3(a).

To verify the bandwidth of the proposed system, the wavelength components of the database in the experiment range from 1540 nm to 1565 nm at intervals of 1 nm, whose range is limited by the operating bandwidth of AOM. LUT is launched to the system and the results are shown in Fig.3(b). It shows that Rayleigh speckle based wavemeter has a large bandwidth.

4. Conclusion

We propose a novel high-resolution wavemeter utilizing Rayleigh speckle obtained from a standard single-mode fiber by OTDR. It is experimentally demonstrated that there exists an inverse relation between pulse width and wavelength resolution. The 6 fm resolution with 2 μs pulse width and the measurement results cross 25 nm bandwidth are validated in the experiment. Experimental results show that Rayleigh speckle based wavemeter has the capability to resolve multi-wavelength lightwave with high-resolution. The proposed novel all-fiber system provides a prospect for compact wavemeter with the advantages of cost-effectiveness, high-resolution and large bandwidth.

Acknowledgment This research was supported by National Key R&D Program of China under Grant 2017YFB0405500, and National Natural Science Foundation of China (NSFC) under Grant 61775132, 61735015, 61620106015, and the Open Projects Foundations of Yangtze Optical Fiber and Cable Joint Stock Limited Company (YOFC) under Grant SKLD1805.

References

1. R. W. Wood, The London, Edinburgh, Dublin Philos. Mag. J. Sci. **4**, 396 (1902).
2. X. Zhaochun, W. Zhanglei, S. Michael, B. David, F. Stephen, and A. Ali, Opt. Express **11**, 2126 (2003).
3. B. Redding, M. Alam, M. Seifert, and H. Cao, Optica. **1**, 175 (2014).
4. N. K. Metzger, R. Spesyvtsev, G. D. Bruce, B. Miller, G. T. Maker, G. Malcolm, M. Mazilu, and K. Dholakia, Nat. Commun. **8**, 15610 (2017).
5. J. Zhou, Z. Pan, Q. Ye, H. Cai, R. Qu, and Z. Fang, J. lightwave technology **31**, 2947 (2013).
6. A. Masoudi and T. P. Newson, Opt. express **25**, 32021 (2017).