SCIENCE CHINA
Information Sciences

• **Supplementary File** •

Spatial resolution improved OFDM-BOTDA utilizing frequency-division-multiplexed Brillouin phase/gain spectrum

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Appendix A Multiple K spectrum

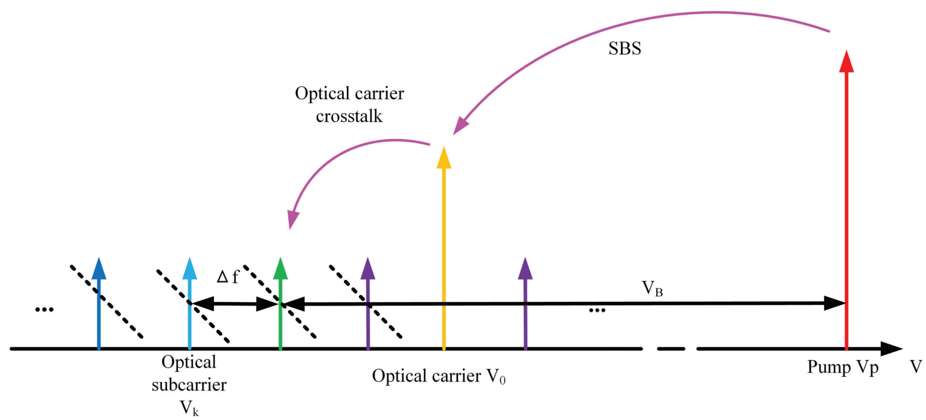

Figure A1 Illustration of multiple K spectrum in BOTDA using OFDM probe and optical carrier crosstalk.

In BOTDA using OFDM probe, every single subcarrier can be used for K spectrum sensing, thus naturally constructing a multiple K spectrum, as shown in Figure A1. The OFDM consists of an optical carrier and multiple subcarriers, with a frequency spacing of adjacent subcarriers Δf. If the frequency detuning between one of the subcarriers and the pump light is close to the BFS of the optical fiber, as is the case in Figure A1, the green subcarrier is chosen for BFS calculation. When the local BFS changes, the adjacent subcarrier may be closer and its K value is more appropriate for BFS extraction, since the BFS error increases with the frequency detuning. Thus, the multiple K spectrum using OFDM probe offers two distinct advantages. First, it can be guaranteed that at least one subcarrier is closer to the center of K spectrum, leading to a higher measurement accuracy. Second, the dynamic range can be greatly improved. Above all, the multiple K spectrum can improve the measurement range, accuracy, and most of all, the spatial resolution, since the subcarrier spacing can be increased to a quite high extent.

Appendix B Simulation on optical carrier crosstalk

To implement a direct detection BOTDA using OFDM probe, the optical carrier serves as a local reference tone. It should be noted that the optical carrier will also interact with the pump pulse though SBS, and the induced amplitude and phase change would transfer to the subcarriers during direct detection process. This kind of crosstalk becomes inevitable in K spectrum measurement since it may distort the shape of BGS and BFS. In this case, the received optical signal should be modified as:

$$s\left(t\right) = e^{j2\pi f_0 t} \cdot \mathrm{e}^{\left(g_0 + j\phi_0\right)} + \alpha \cdot e^{j2\pi f_0 t} \cdot \sum_{k=0}^{N-1} \mathrm{e}^{\left(g_k + j\phi_k\right)} c_k e^{j2\pi f_k t} \tag{B1}$$

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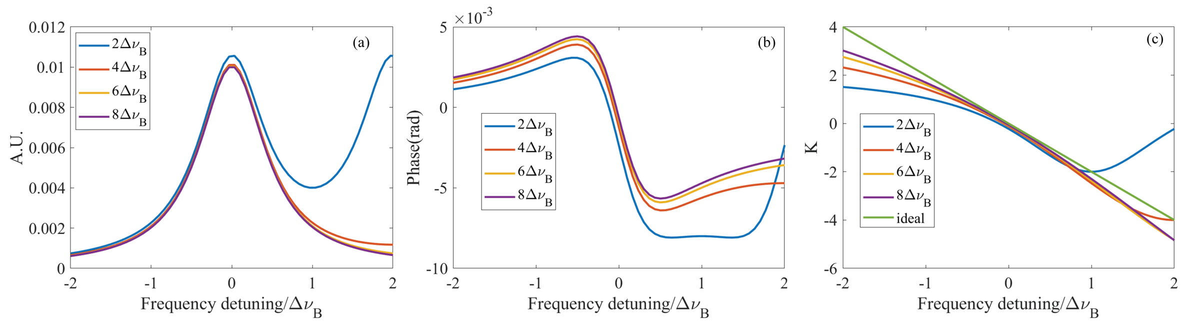

Figure B1 Simulated optical carrier crosstalk on (a) Brillouin gain spectrum, (b) Brillouin phase spectrum, and (c) K spectrum of a given subcarrier.

where g_0 and ϕ_0 are the Brillouin gain and phase imposed on the optical carrier, g_k and ϕ_k are the Brillouin gain and phase on the subcarriers. The current signal after a photodetector is denoted as follows:

$$I(t) = s(t)\cdot s^*(t) = e^{2g_0} + 2\alpha\cdot\mathrm{Re}\left\{\sum_{k=0}^{N-1}\left[\underbrace{\left[e^{(g_0+g_k)+j(\phi_k-\phi_0)}\cdot c_k\right]}_{r_k} e^{j2\pi f_k t}\right]\right\}$$
$$+|\alpha|^2\sum_{k1=0}^{N-1}\sum_{k2=0}^{N-1}\left[\left[e^{(g_{k1}+g_{k2})+j(\phi_{k1}-\phi_{k2})}\cdot c_{k2}^* c_{k1}\right] e^{j2\pi(f_{k1}-f_{k2})t}\right] \tag{B2}$$

Finally, by FFT and channel estimation, the complex Brillouin spectrum can be obtained:

$$H_k = \frac{r_k}{c_k} = e^{(g_0+g_k)+j(\phi_k-\phi_0)} \tag{B3}$$

From Eq. (B3), it can be seen that the optical carrier crosstalk introduces an upshift of the BGS and downshift of the BPS. The shift may not affect BFS extraction based on curve fitting methods using BGS, because the line shape and symmetry are not defected. However, it may result in a nonlinear K spectrum and influence the BFS calculation using its slope. Moreover, the optical carrier crosstalk varies dependent on the local BFS, which will cause further impairments in practical sensing. Considering a certain subcarrier k_0 , the measured Brillouin gain and phase corresponding to BFS change can be expressed as follows:

$$g_{k0} + g_0 = \frac{g_B\Delta v_B^2}{\Delta v_B{}^2 + 4\Delta v^2} + \frac{g_B\Delta v_B^2}{\Delta v_B{}^2 + 4(\Delta v - f_{RF})^2} \tag{B4}$$

$$\phi_{k0} - \phi_0 = -\frac{2g_B\Delta v\Delta v_B}{\Delta v_B{}^2 + 4\Delta v^2} - \frac{-2g_B\Delta v\Delta v_B}{\Delta v_B{}^2 + 4(\Delta v - f_{RF})^2} \tag{B5}$$

where f_{RF} is the frequency offset between the optical carrier and subcarrier k_0 . From Eq. (B4) and Eq. (B5), it can be seen that the influence of the optical carrier crosstalk becomes more severe with the frequency detuning increasing towards the positive direction. And larger f_{RF} can apparently mitigate the crosstalk. We numerically simulated the relationship between the crosstalk and the optical carrier frequency offset f_{RF} . As can be seen in Figure B1, the BGS and BPS is obviously up shifted when the f_{RF} is smaller, and greater distortion occurs on the positive direction of frequency detuning. Besides, the K spectrum becomes more nonlinear and the linear range is also limited by smaller f_{RF} . Compared with the ideal spectrum, the slope is slightly larger, which may cause measurement error. All the results show that the optical carrier crosstalk should be eliminated and the frequency offset between the optical carrier and subcarriers should be at least 4 times of the Brillouin linewidth to neglect the crosstalk.

Appendix C Experimental setup

An external cavity optical fiber laser is used as the light source, of which the central wavelength is about 1550 nm and optical power is about 13 dBm. A 50:50 optical fiber coupler is used to split the light into two branches as pump and probe light. The probe light is firstly directed to an electro-optic intensity modulator (EOM1) driven by a 10.5 GHz RF signal from a microwave source (MS), then modulated by EOM2 to generate OFDM signal. The real-valued digital OFDM signal has a total bandwith of 500 MHz with a number of 32 subcarriers, but 15 effective subcarriers. The subcarriers are mapped by BPSK constellation to reduce the peak-to-average power ratio. Besides, the subcarrier interleaving technique (i.e. the even subcarriers are unused) is applied to mitigate the noise from subcarriers interference, thus the number of effective subcarriers for sensing is halved. It should be noted that the spatial resolution is mainly determined by the nominal subcarrier spacing. The pump pulse is generated by a semiconductor optical amplifier (SOA). The pulse duration is set 50 ns to make a balance between the dynamic range and spatial resolution for better performance of K spectrum. The fiber under test (FUT) is a spool of about 1.8 km single mode fiber with the local BFS around 10.715 GHz, and a 50 m fiber splicing at the end with BFS around 10.735 GHz.

Appendix D Experimental results

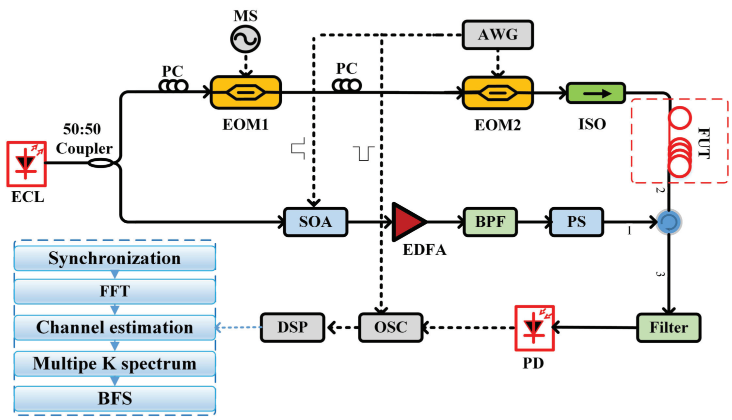

Figure C1 Experimental setup. ECL, external cavity laser; PC, polarization controller; MS, microwave source; EOM, electro-optic modulator; AWG, arbitrary waveform generator; ISO, isolator; SOA, semiconductor optical amplifier; EDFA, Erbium doped fiber amplifier; BPF, bandpass filter; PS, polarization scramble; PD, photodiode; OSC, oscilloscope; DSP, digital signal processing; FUT, fiber under test.

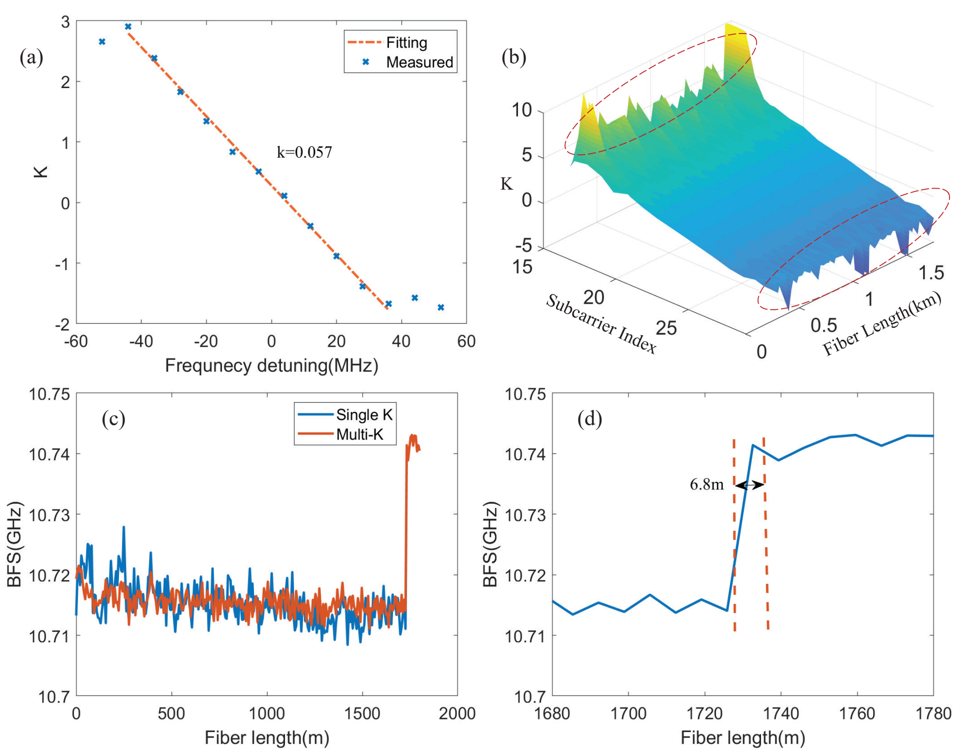

Figure D1 (a) The measured K spectrum of a certain position. (b) 3-D distribution along the fiber. (c) The distributed BFS along the fiber using single K spectrum and multiple K spectrum. (d) The BFS distribution at the fiber end.