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RESEARCH ARTICLE

Investigation on Brillouin scattering characteristics in photonic crystal fibers

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Abstract Brillouin scattering characteristics of photonic crystal fibers (PCFs) are investigated theoretically and experimentally in this paper. The results of two kinds of PCFs are compared and discussed, the influences of size of fiber core on the acoustic modes and hence on the Brillouin resonance peaks are explained. Furthermore, the improvement for our research is also presented.

Keywords photonic crystal fiber (PCF), stimulated Brillouin scattering (SBS), acoustic wave

1 Introduction

Brillouin scattering in fibers has attracted lots of attention for its potential usage in sensing [1], single mode amplification [2], multi-wavelength fiber lasers [3] and slow light [4]. Therefore, a lot of research works on Brillouin scattering in fibers have been done and reported in theory and experiment. People have explored many methods to predict the characteristics of Brillouin scattering in different fibers from solving the acoustic-optical interaction equation [5]. Along with the invention of photonic crystal fiber (PCF), which is a special kind of optical fiber with air holes running along the length of the fibers, more methods based on acoustic crystal and acoustic band-gap theory have been introduced [6]. However, these methods are complicated and need a large quantity of calculations.

In this paper, the Brillouin scattering characteristics of two types of PCFs are investigated theoretically and experimentally. A relatively simple method to simulate the basic property of Brillouin scattering spectrum is introduced and applied. Also, we proposed an experimental setup to test the Brillouin related parameters in PCFs, including threshold, frequency shift, and full gain spectrum. Furthermore, the results of simulation and experiment are compared and discussed focused on the influence of fiber structure on the shape of Brillouin spectrum.

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2 Theory model

The longitudinal acoustic wave interacts with optical wave and therefore accounts for the main components in Brillouin spectrum, and its displacement $u(x,y)$ satisfies the two-dimensional scalar equation [7]:

$$\nabla_t^2 u + \left(\frac{\omega_{ao}^2}{v_L^2} - \beta_{ao}^2\right) u = 0, \tag{1}$$

where ∇_t^2 is the transverse Laplacian operator in the x-y plane, ω_{ao} is the angular frequency of the acoustic wave, v_L is the longitudinal acoustic velocity, and β_{ao} is the propagation constant of the mode. Only when the phase matching condition $2\beta_{op} = \beta_{ao}$ is satisfied, the backward Brillouin scattering happens, with β_{op} being the propagation constant of optical mode. The Brillouin frequency shift f_B is

$$f_B = \frac{2n_{eff}v_{eff}}{\lambda}, \tag{2}$$

where λ is the pump wavelength, n_{eff} is the effective index of optical mode, usually the Gaussian-like fundamental mode. v_{eff} is the effective mode velocity of the longitudinal acoustic mode interacting with the optical mode.

The solution of Eq. (1) gives the field patterns and along with the effective velocity of each mode, which is obtained by utilizing a commercial finite-element method solver.

By employing proper parameters including boundary condition and mesh size, a series of acoustic modes can be

acquired. Once the pattern of acoustic mode has been evaluated, the following equation is used to determine the efficiency of the back-scattering process

$$A_{\text{ao-op}} = \left(\frac{\int |E|^2 \mathrm{d}x\mathrm{d}y}{\int |E|^2 u \mathrm{d}x\mathrm{d}y} \right)^2 \int u^2 \mathrm{d}x\mathrm{d}y, \tag{3}$$

where, $A_{\text{co-op}}$ is effective acoustic-optical interaction area, which is evaluated by the overlap integral between acoustic mode and optical mode, where $E(x,y)$ is the distribution pattern of optical field obtained from the 2-D scalar wave equation.

The ith-order acoustic mode contributes to a Brillouin resonance peak with the distribution function,

$$g_i(f) = \frac{4\pi n_{\text{eff}}^8 p_{12}^2}{\lambda^3 \rho c f_{\text{B},i} \Delta f} \frac{\Delta f^2}{4(f - f_{\text{B},i}) + \Delta f^2} \frac{1}{A_{\text{ao-op}}}, \tag{4}$$

where p_{12} is the longitudinal elasto-optic coefficient, ρ is the material density, c is the speed of light in vacuum, Δf is the full linewidth at the half maximum (FWHM) bandwidth of the peak, which is assumed to be the same 40 MHz for all the resonance peaks. Since the acoustic modes are statistically independent, the total Brillouin spectrum is the sum of each mode:

$$g(f) = \sum_i g_i(f). \tag{5}$$

3 Experimental setup

The experimental setup in this measurement is shown in Fig. 1. The tunable laser used as light source is split into two beams. One beam is amplified by an erbium-doped fiber amplifier (EDFA) and used as pump light, injecting into the PCF through a circulator. Another beam is used as signal light, which is modulated by an electro-optic intensity modulator (EOIM). By loading a microwave signal of around 10 GHz and adjusting the voltage to the EOIM, the signal light can be modulated to create two sideband frequencies located on both sides of the original signal, one is frequency down-shifted and the other is up-shifted, and the former one is the probe signal we need. The EDFA1 and attenuator are used to amplify the signal to our required power level. When measuring, by injecting a pump light with power lower than the stimulated Brillouin scattering threshold (in undepleted region) into the PCF, signal entering the fiber from the other end of the fiber will be amplified. By applying such Brillouin amplification principle, we convert small frequency change into more obvious change in wavelength power. Scanning the signal of microwave generator over a certain range, a full Brillouin scattering spectrum will be obtained.

4 Results and discussion

We test two sections of air-hole PCF, whose cross-section microscope pictures and parameters are shown in Fig. 2 and Table 1, respectively. The fibers were fabricated by Yangtze Optical Fiber and Cable Co., Ltd. of China. As seen from Fig. 2, these two kinds of fibers have similar structure and are both made by pure silica, but the diameter of the air-hole is very different, which accounts for the difference in effective optical mode area, fiber loss and some other characteristics.

The measured Brillouin spectra of the two kinds of fibers are depicted in Figs. 3(a) and 3(b), respectively. As seen in the picture, except for some noise and errors induced during the measurement, experimental results fit simulation results quite well. The acoustic modes we used in the simulation are listed in Tables 2 and 3.

As we can see in Tables 2 and 3, acoustic modes in the PCF with smaller cores separate more widely, which

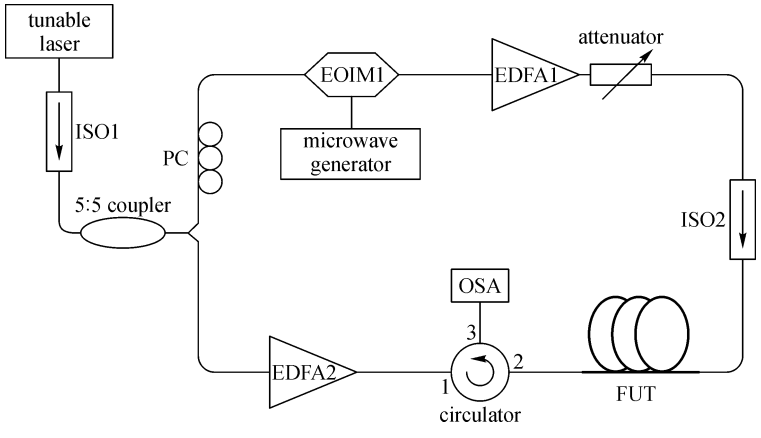


Fig. 1 Experimental setup (PC: polarization controller; ISO: isolator; OSA; optical spectrum analyzer; FUT: fiber under test)

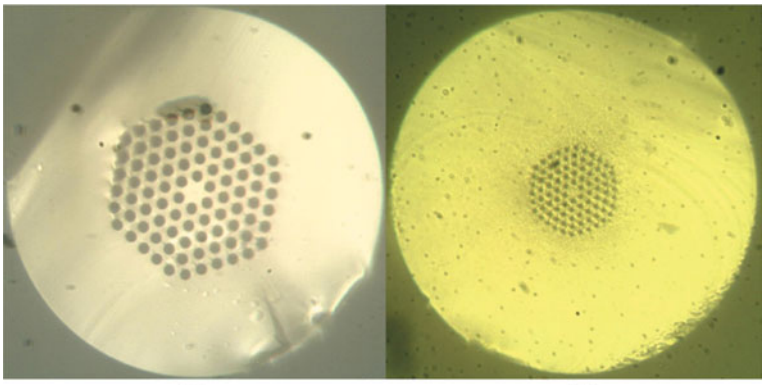


Fig. 2 Two kinds of cross-section microscope pictures of fiber. (a) PCF A; (b) PCF B

Table 1 Fiber parameters

fiber parameters	PCF A	PCF B
hole diameter d/μm	3.900	2.100
normalized diameter $\frac{d}{\Lambda}$	0.700	0.700
outer diameter/μm	125.000	125.000
effective mode area A_{eff}/μm^2	82.900	26.400
effective refractive index N_{eff}	1.437	1.422
fiber length/km	2.000	1.500
fiber loss/(dB/km@1550 nm)	1.500	5.700
total loss/dB	4.000	10.000

results in the separation of Brillouin resonance peaks in the frequency spectrum. The results accord with Refs. [8,9]. On the other hand, except for some measurement errors, there are still obvious differences between theoretical and experimental results, which can be attributed to the parameter sets in the simulation deviating from those of the actual PCFs.

The air-silica "hard" wall combines longitudinal acoustic mode and transverse acoustic mode, making the modes become more hybrid, and the component of the transverse mode will display in the Brillouin spectrum at around 7 GHz [8], determined by the velocity of transverse modes, which are not discussed in this paper. To make the prediction more suitable, more acoustic modes should be taken into consideration, including more cladding modes. As to the experimental setup, the optical spectrum analyzer should be replaced by a high-frequency photodetector and oscilloscope, which can monitor the fine structure of Brillouin spectrum timely.

5 Conclusions

The Brillouin scattering characteristics of two sections of different types of PCFs are investigated theoretically and experimentally. The experimental results match the theoretical results well, which validates that our simulation method is an easy and effective method to predict the basic characteristics of the Brillouin spectrum. To make the prediction more precise, the effect of transverse acoustic mode should be taken into consideration.

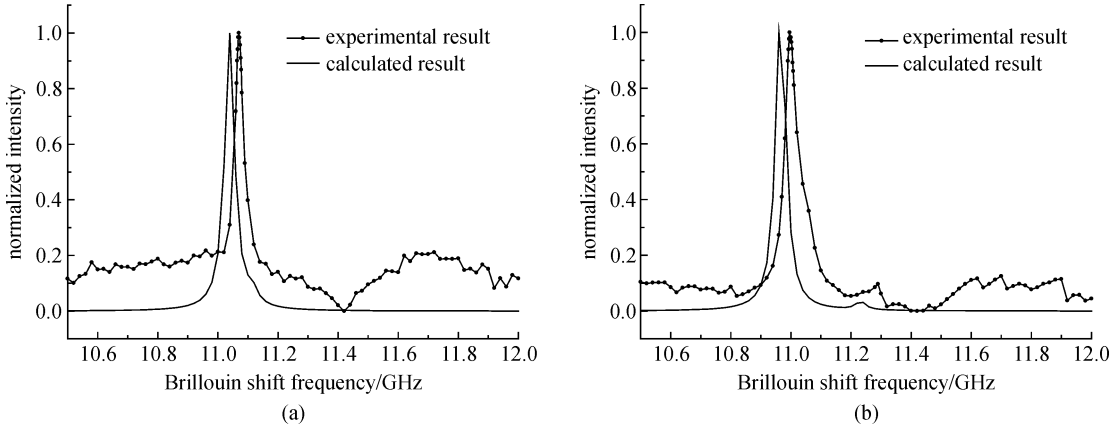


Fig. 3 Simulation and experimental results for fiber A (a) and fiber B (b)

Table 2 Acoustic modes in simulation for fiber A

acoustic mode	velocity/(m·s^{-1})	Brillouin shift/GHz	$A_{\text{co-op}}$/μm^2
L_{01}	5953.9	11.039	13.8
L_{02}	5954.0	11.067	6.4×10^{11}
L_{03}	5987.7	11.102	9.4×10^{5}
L_{10}	5994.3	11.114	280.0

Table 3 Acoustic modes in simulation for fiber B

acoustic mode	velocity/(m·s^{-1})	Brillouin shift/GHz	$A_{\text{co-op}}$/μm^2
L_{01}	5978.5	10.966	4.3
L_{02}	6031.6	11.064	5.4×10^{12}
L_{03}	6098.9	11.187	3.5×10^{5}
L_{10}	6123.4	11.232	157.0

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