Direct Electrostriction Measurement using SPM for Fiber Type Identification

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Abstract: We present a simple technique for in-field determination of fiber types through the measurement of electrostriction effect based on self-phase modulation.

1. Introduction:

An optical signal in an optical fiber can create sound waves propagating in both longitudinal and radial directions. The interaction between the optical signal and the longitudinal sound wave can cause significant optical backscattering in a process known as stimulated Brillouin scattering (SBS) [1], which is equivalent to a nonlinear loss. Whereas the acoustic wave propagating in the radial direction is bounced back and forth between the center and circumference of the cladding/coating interface [2, 3] to create an acoustic standing wave, which modulates the refractive index of the fiber. This results in a complex modulation of the forward propagated optical signal in the frequency region typically below 1 GHz. This effect is commonly referred to as electrostriction. The frequency dependence of electrostriction in optical fiber is primarily determined by the mechanical properties of silica material and the geometry of optical fiber. This provides a mechanism for fiber type identification through measuring the frequency dependence of electrostriction. In practical optical networks, different types of optical fibers may coexist, and simple techniques to identify fiber types are desirable for network operation and performance optimization.

Measurements of frequency-dependent electrostriction in optical fibers have been reported, primarily using cross-phase modulation (XPM) in a pump-probe configuration. In this case, phase modulation on the continuous-wave (CW) probe introduced by an intensity-modulated pump is measured to determine the real part of the frequency-dependent nonlinear refractive index of electrostriction, n_{2e} [4 – 6]. Self-phase modulation (SPM) can also be used to characterize n_{2e} by measuring the complex optical field change of an intensity modulated optical signal traveling through a fiber. SPM only requires a single carrier with a modulation bandwidth on the order of 1 GHz to probe electrostriction. However, at the receiver it is quite challenging to separate the very weak perturbation caused by electrostriction from the applied large signal modulation and four-wave mixing (FWM) among different frequency components.

In this paper, we demonstrated a simple technique to determine fiber types through electrostriction effect measured from SPM. An optical signal is intensity-modulated in a linear frequency chirped waveform to avoid the impact of FWM. Because the imaginary part of nonlinear index n_{2e} is antisymmetric [2, 6], the impact of electrostriction can be extracted by subtracting the coherently detected complex field of optical signal from its complex conjugate. We show that the envelope of frequency-dependent electrostriction resonance precisely follows a normalized Maxwellian distribution, and this allows using a single parameter to define the fiber type.

2. Experiment and results

To demonstrate the concept, we utilized a commercial digital coherent transceiver in an experimental setup as shown in Fig. 1. A digitally created linear-chirp waveform is used to modulate the intensity of the optical carrier in the transmitter (Tx) at 1549.3 nm wavelength. The complex optical field is detected by a coherent receiver (Rx) after the optical fiber. The waveform is linearly chirped from 25 MHz to 1.5 GHz within a time window of approximately 1.93 µs. Although the Tx used in the experiment has 68 GS/s sampling rate, a lower speed Tx would also be sufficient. In order to avoid edge effect in the Fourier transform, the waveform is apodized with a 10^{th} order super-Gaussian digital filter in the time domain. The modulated optical signal is sent to an optical fiber under-test with an average power of approximately 6dBm. At the fiber output, the coherent receiver recovers the complex field of the optical signal through in-phase/quadrature (I/Q) detection after mixing with an optical local oscillator (LO). The recovered complex field is digitized and recorded for off-line analysis. The inset at the left side of Fig.1 illustrates the waveform (top) and the spectrum (bottom) of the optical field. With SPM in the fiber, the complex field of the optical signal is affected by its own intensity. Although the optical power waveform is ideally linear chirped, the field has significant high order harmonics. Proper signal processing is required to separate electrostriction-induced waveform perturbation, illustrated in the inset of Fig.1 (right side), from the original large-signal modulation.

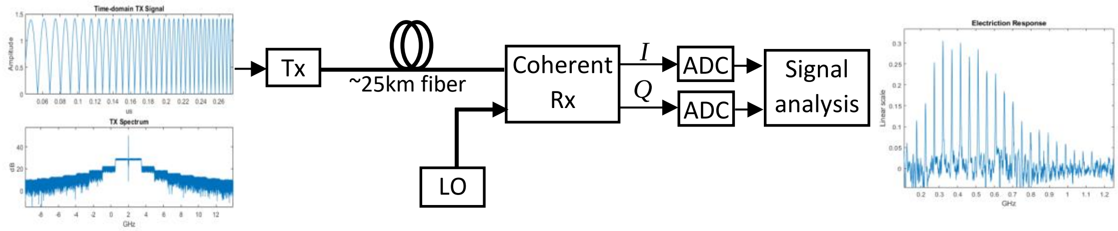

Fig 1. Experimental Setup

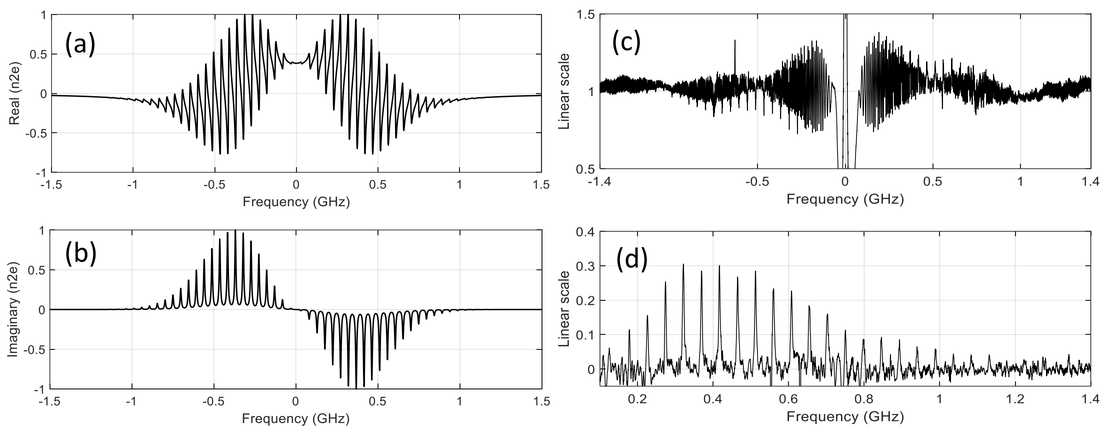

Fig 2. (a) and (b): amplitude normalized real and imaginary parts of n_{2e}. (c) spectrum of recovered complex optical field with 1.5GHz linear chirp. (d) frequency-dependent loss due to electrostriction obtained by subtracting the spectrum shown in (c) from its complex conjugate.

Fig.2 (a) and (b) show the real and imaginary parts of n_{2e} theoretically predicted in [2]. Fig.2(c) shows the amplitude of the complex optical spectrum measured with the coherent homodyne receiver after the fiber. Within the chirp bandwidth of 25 MHz -1.5 GHz, the resonance signature of electrostriction is buried under the impact of phase modulation and interference with high order harmonics. Taking advantage of the anti-symmetry of the imaginary part of n_{2e} as indicated in Fig.2(b), electrostriction induced frequency-dependent loss can be obtained by subtracting the spectrum shown in Fig.2(c) from its complex conjugate, and the result is shown in Fig.2(d) (only on the positive frequency side). The frequencies of electrostriction resonance peaks and their envelope shown in Fig.2(d) are determined by the imaginary part of n_{2e}. More specifically, the frequencies of the acoustic modes are primarily determined by the sound velocity and the radius of the fiber cladding, whereas the envelope is more related to the fiber core radius and the damping rate of the material [6]. The measured result shown in Fig.2(d) is unique for each specific fiber type, which provides a mechanism for fiber type identification.

While most of the fibers have a standard cladding diameter of 125 µm, the core diameter is different for different types of fibers. We have measured 3 different fiber types, including TrueWave fiber, TeraWave fiber and standard single-mode fiber (SMF), and the results are normalized and shown as dotted lines in Fig.3 (a), (b), and (c), respectively. The solid lines in Fig.3 (a), (b), and (c), are normalized imaginary part of n_{2e} calculated by adjusting fiber parameters to best fit the measured results of each fiber type. The fiber parameters used are 3740 [m/s] for longitudinal sound velocity, 5960 [m/s] shear sound velocity, and [3.03, 62.55], [4.69, 62.5], [3.66, 62.35] are [core, cladding] radius in µm for TrueWave, TeraWave and standard SMF, respectively. The normalized envelopes of electrostriction resonances shown in Fig. 3 (a-c) closely follow a Maxwellian distribution $P(f) = \eta \cdot \frac{f^2}{q^3} \exp\left(-\frac{f^2}{2 \cdot q^2}\right)$ normalized to its maximum amplitude, where f is the frequency, and $\eta = 1/P_{max}$ is the normalization factor with P_{max} the maximum value of $P(f)$ which happens at a frequency $f = \sqrt{2}q$. The dashed line in Fig.3 (a-c) shows the best fit of Maxwellian distribution to the envelope of electrostriction resonances of each fiber. As q is a parameter that uniquely determines the shape of a Maxwellian distribution, the best fit between the envelope of measured electrostriction resonances and Maxwellian distribution yields an optimum q value for each fiber type.

Fig.3(d) shows the normalized mean-square-error (MSE) between the theoretical peak amplitudes of the imaginary part of n_{2e} as the function of the frequency and Maxwellian distribution with different q values for the three fiber types considered here. The normalized minimum MSE value at the optimum q for each fiber type is always lower than 10^{-5} in the numerical fitting, indicating that there must be an underlining physical mechanism, which is worthy of further investigation. Fig.3(e) shows the normalized MSE between the measured electrostriction resonances and Maxwellian distributions for the three fiber types using q as a variable. Although the minimum errors are increased to a level of approximately 0.5%, an optimum q value corresponding to the minimum MSE can still be clearly identified for each fiber type. Each fiber was measured for 3 times and their q values are 204 ± 2 MHz, 261 ± 2 MHz, and 314 ± 3 MHz, for TrueWave, TeraWave and standard SMF, respectively.

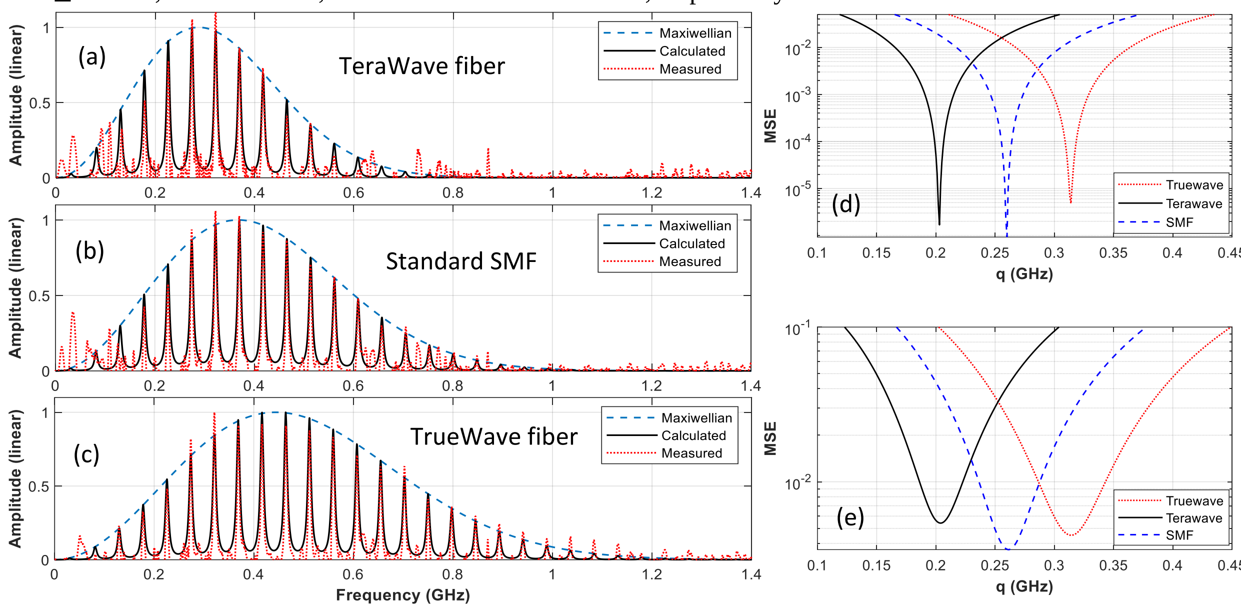

Fig 3. (a – c): measured (dotted lines) and calculated (solid lines) frequency-dependent loss of electrostriction for 3 types of fibers. Dashed lines: Maxwellian fitting. (d) normalized MSE between calculated envelope of electrostriction resonance and Maxwellian distribution with varying q value, (e) normalized MSE between measured envelope of frequency dependent loss and Maxwellian distribution with varying q value

3. Conclusion

We have experimentally demonstrated a simple technique to identify fiber types through the measurement of SPM induced electrostriction resonance. Taking advantage of anti-symmetry of the imaginary part of nonlinear index n_{2e}, the signal to noise ratio (SNR) can be significantly improved in the measurement of electrostriction-induced frequency-dependent loss. We show that the envelope of the electrostriction resonances closely follows a normalized Maxwellian distribution, so that a unique q value is adequate to identify the fiber type. The SPM based measurement technique only requires intensity modulation of a relatively low speed Tx with the bandwidth on the order of a GHz.

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