A technique that exploits different pulse widths delivers the best spatial resolution and sensing length to date for distributed sensors based on scattering of light by sound waves.

Twenty years have passed since Brillouin optical time domain analysis (BOTDA) was first used to detect 3°C temperature resolution and 100m spatial resolution over a 1.2km optical fiber (the Brillouin frequency is proportional to temperature and strain). These ‘distributed’ sensors have enormous potential for monitoring the health of large civil structures such as dams, bridges, and pipelines, which require long sensing length for coverage in two and three dimensions. Because of their ability to locate and identify microcracks and other anomalies, distributed sensors can help to prevent disasters due to corrosion of steel and concrete interfaces, deformation of pipelines, and gas, oil, and water leaks in pipes. However, achieving high-performance distributed sensors with high spatial resolution (<1m) and high strain resolution (10με) over long sensing lengths (>10km) poses a considerable challenge.

Early development of distributed Brillouin sensors over distances employed a loss rather than a gain technique. In the gain process, the pumped pulse transmits energy to the probe wave through stimulated Brillouin scattering, and the pump wave can quickly be depleted. Brillouin loss, however, uses a continuous wave as pump, which is more robust. In 1995, we achieved the longest sensing length to date of 51km, with 5m spatial resolution and 1°C temperature resolution. Figure 1(a) shows the Brillouin gain signal and Figure 1(b) the linewidth of the Brillouin gain versus the spatial resolution from these experiments.

It is very clear that shorter spatial resolution results in low gain: see Figure 1(a). Indeed, achieving a high signal-to-noise ratio requires the narrow spectral width typical of a large pulse: see Figure 1(b). But high power and greater pulse width distort the Brillouin spectrum. Consequently, lower power is preferable.

The spatial resolution of the distributed Brillouin scattering fiber sensor is limited to 1m, which is equivalent to the relaxation time of an acoustic wave (10ns). When a short pulse (<5ns) is used for submeter spatial resolution, the Brillouin gain becomes very weak. The broadened Brillouin spectrum determined by the convolution of the pulse and natural Brillouin gain spectrum prohibits short pulses, except for those with a small DC level that provides prepumping for the acoustic field. This produces a Brillouin spectrum whose width is close to the natural Brillouin spectrum. However, the DC-level-induced prepumped acoustic

Figure 1. (a) Peak Brillouin loss as a function of pulse duration. (b) Brillouin spectral width vs. pulse width.

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The working principle of differential pulse-width pair Brillouin optical time domain analysis (DPP-BOTDA) sensor. I: Intensity. 0: Initial fiber point. t: Time. \( t_1, t_2 \): Pulse width. \( \delta t \): Pulse-width difference. \( \delta z \): \( \delta t \) equivalent length. \( c \): Speed of light in fiber.

Figure 2. Working principle of differential pulse-width pair Brillouin optical time domain analysis (DPP-BOTDA) sensor. I: Intensity. 0: Initial fiber point. t: Time. \( t_1, t_2 \): Pulse width. \( \delta t \): Pulse-width difference. \( \delta z \): \( \delta t \) equivalent length. \( c \): Speed of light in fiber.

wave tends to deplete the Stokes signal in the Brillouin loss-based sensor over the long sensing length, which limits the use of prepumping for such applications.

Because of the high gain in the long pulse, we used two large pulses with slightly different pulse widths to measure BOTDA in the time domain. Then we subtracted the results of two different pulses at each scanned Brillouin frequency to give the differential gain at every fiber position. This new technique, called differential pulse-width pair (DPP)-based BOTDA,\(^1\) is shown schematically in Figure 2, where \( \delta t \) is the pulse-width difference, and \( \delta z \) is its equivalent length. This approach has been used to demonstrate 25km sensing length on dispersion-shifted fiber and submeter (50cm) spatial resolution\(^1\) for a strain resolution of 10\( \mu \)E (i.e., 10\( \mu \)m strain over a length of 1m).

Achieving even longer sensing lengths (>30km) calls for coded pulses to meet the requirement of low power. Using DPP-BOTDA with an RZ (return-to-zero)-coded pulse and a 55/60ns pulse pair, we measured a stress level of 50cm over 50km sensing length (see Figure 3). The uncertainty of the Brillouin frequency shift is 0.7MHz,\(^1\) which is proportional to a strain resolution of 12\( \mu \)m. These findings represent the best results obtained thus far (and the best balance of trade-offs) for the combination of sensing length with spatial and temperature resolution using Brillouin scattering-based distributed sensors.

We plan to further develop extended sensing length by adding inline fiber amplifiers, which help to sustain a high signal-to-noise ratio over great distances.