Measurement of Rayleigh Backscattering at 1.55 μm with a 32 μm Spatial Resolution

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Rayleigh backscattering at a wavelength of 1.55 μm is measured in standard single-mode fiber with a spatial resolution of 32 μm and a dynamic range of over 30 dB. A minimum reflection sensitivity of -148 dB is the best reported to date using optical low-coherence reflectometry.

1 Introduction

In optical time domain reflectometry, the measurement of Rayleigh backscattering (RBS) is important in the determination of fiber attenuation, splice loss, and the location of non-reflecting fiber breaks. In conventional pulsed techniques, the measurement of RBS becomes more difficult as spatial resolution is improved. Higher spatial resolution simultaneously results in lower levels of RBS power and increased noise power due to larger receiver bandwidths. White light interferometry or optical low-coherence reflectometry (OLCR) [1]-[5] provides a technique that allows several orders of magnitude improvement in both sensitivity and spatial resolution compared to conventional time domain methods. Spatial resolutions of tens of microns can easily be obtained [3]-[5], corresponding to equivalent optical pulse widths of a few hundred femtoseconds. For these small spatial resolutions, average RBS levels for standard telecommunications fiber are on the order of -115 dB. Reflection sensitivities have been limited to values close to the RBS levels due to the intensity noise of low-coherence optical sources. However, a reflection sensitivity of -136 dB (using a 3 Hz bandwidth) has recently been demonstrated at a wavelength of 1.3 μm using a high-power superluminescent diode and a balanced detection scheme to subtract the intensity noise [5],[6].

In this paper we report an optical reflection sensitivity of -148 dB (in a 3 Hz bandwidth), which we believe is the highest sensitivity ever demonstrated using optical low-coherence reflectometry. This reflection sensitivity was achieved using 10 mW of amplified spontaneous emission from a two-pass diode-pumped erbium-doped fiber superfluorescent source [7]. Rayleigh backscattering is measured for the first time at a wavelength of 1.55 μm with 32 μm spatial resolution and more than 30 dB of dynamic range between the RBS and the noise floor.

2 Experiment

The experimental arrangement used to perform the Rayleigh backscattering measurements is shown in figure 1. The amplified spontaneous emission (ASE) from an erbium-doped fiber produced 10 mW of optical power with a spectral width of 12 nm centered at a wavelength of 1.55 μm. After passing through a 3 dB directional coupler (C1) the optical signal is divided into the two arms of the interferometer. The signal in one arm passes through an in-line fiber polarization controller (PC) and a piezoelectric (PZT) optical phase shifter before proceeding to the component or device under test (DUT). The other arm has a variable time delay provided by a retroreflecting mirror mounted to a motorized translation stage with 0.1 μm resolution and a scan range of 150 mm. The optical phase shifter is sawtooth ramped over a range of 180 degrees [4] producing a serrodyne frequency shift on the returning signal. When the time delay of the mirror path matches the time delay of a reflection from the DUT arm, coherent interference occurs producing a beat signal at the serrodyne frequency whose strength is dependent on the magnitude of the reflection. The value of the frequency shift was chosen to coincide with a minimum in the receiver noise floor. In coupling to the mirror, the fiber ends were cleaved at angles to minimize Fresnel reflections which can raise the measurement noise floor.

The power spectrum of the subtracted output was measured using a HP3585B electrical spectrum analyzer. Measurements were performed by stepping the mirror in 25 μm increments, and at each location measuring the photocurrent signal within a 3 Hz bandwidth centered at the serrodyne frequency shift of 75 Hz. The total measurement time was about

1.4 seconds per 25 μm step. Although the measurement time could have been smaller, the extra time was required for mirror stabilization and data transfer to a computer. In other OLCR schemes, the mirror is moved at a constant velocity to produce both the variable time delay and a Doppler frequency shift for the heterodyne detection. This method was not suitable for our measurements since the mirror velocity jitter produced frequency deviations larger than the 3 Hz detection bandwidth.

The system described was used to measure Rayleigh backscattering along a telecommunications-grade single-mode fiber at 1.55 μm. Figure 2 shows the resulting backscatter near the end of an angle-cleaved fiber. The spatial resolution (FWHM) was measured to be 46±3 μm (distance of mirror travel in air), corresponding to a distance within the fiber of 32 μm. This spatial resolution is determined by the coherence length of the source and the differential dispersion between the two arms of the interferometer. Figure 2a shows the raw backscattering data before any spatial averaging is performed. The presence of the Rayleigh backscattering is clearly observed up to a distance of 76 mm which identifies the end of the fiber. The large amplitude uncertainty in the Rayleigh backscattering is due to the statistical nature of the scattering sites along the fiber. This variation in the level of the Rayleigh backscattering signal is sometimes referred to as coherence speckle or coherent fading. The spatial variations for this scattering change with a distance approximately equal to the coherence length of the optical source which also determines the minimum spatial resolution of the measurement. The reflectivity scale was calibrated by measuring the Fresnel reflection (i.e. R =-14.7 dB) from a carefully cleaved fiber. The absolute calibration uncertainty is approximately ±2 dB due to uncertainties in polarization adjustment and cleave angle for the reflectivity calibration.

Figure 2b illustrates how spatial averaging can be used to reduce the amplitude uncertainty in the backscattered signal. Each data point in figure 2b is obtained by spatially averaging 200 of the points shown in figure 2a. The resulting amplitude uncertainty in the backscatter is reduced to less than 1 dB at the expense of decreasing the spatial resolution to about 3.4 mm. From figure 2b, the averaged RBS level is about -117 dB. This value corresponds to the scattering captured from a 32 μm length of fiber at the probe wavelength of 1.55 μm. Normalizing to 1 meter gives an RBS level of -72 dB/m which is typical at this wavelength for telecommunication fiber.

The minimum reflection sensitivity of -148±2 dB is also shown in figure 2b. Based on the 1.3 mA of average current from each photodiode, this sensitivity corresponds to about 3 dB above the shot noise limit. The increase in the reflected signal after the end of the angle-cleaved fiber (at a mirror position of 90 mm) is believed to be due to reflected light from the fiber cleave that travels back into the fiber cladding, scatters off the plastic jacket back to the fiber cleave and then recouples back into the fiber core.

Figure 3 shows the change in the level of RBS at a fusion splice between a standard telecommunications fiber and a 400 ppm erbium-doped fiber. As in figure 2, the level of RBS is determined by the coherence length of the source which results in an effective backscatter capture length of 32 μm. Spatial averaging was performed (every 40 data points) resulting in one data point for every millimeter change in mirror position. From figure 3, it can be seen that the Rayleigh backscattering from the erbium-doped fiber is about 10 dB larger than the telecommunications fiber. This increase in scattering is probably due to the additional doping and larger numerical aperture of the erbium-doped fiber which has a core-cladding index difference equal to 0.02 and a core diameter of 3 μm. The results from figure 3 also show that the reflection from the interface of the fusion splice is less than -110 dB. This small value implies that the reflection coefficient from a good fusion splice is negligible compared to the surrounding Rayleigh backscattering.

3 Discussion

Measurement of low level RBS signals in the presence of much larger discrete reflections requires minimization of the "sidelobes" on the autocorrelation tails of the source spectrum. For our measurement system these sidelobes were -60 dB down from a discrete reflection and were due to residual pump signal at the interferometer output. Smaller sidelobe levels should be possible with improved filtering of the pump signal. Although amplitude uncertainty in the RBS signal is large, it can be reduced by the use of spatial averaging. This averaging does not decrease the dynamic range between the RBS and noise floor. With appropriate data processing this allows the possibility of both high spatial resolution when measuring discrete interface reflections and the observation of subtle changes in the level of RBS if high spatial resolution is not required.

4 Conclusions

Rayleigh backscattering measurements were experimentally demonstrated at a wavelength of 1.55 μm in single-mode fiber using optical low-coherence reflectometry with balanced detection for intensity noise subtraction. A superfluorescent noise source was used providing 10 mW of optical input power. With a spatial resolution of 32 μm, the average Rayleigh backscattering signal was - 117 dB which is more than 30 dB larger than the -148 dB system noise floor.

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5 References

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Figures

Figure 1

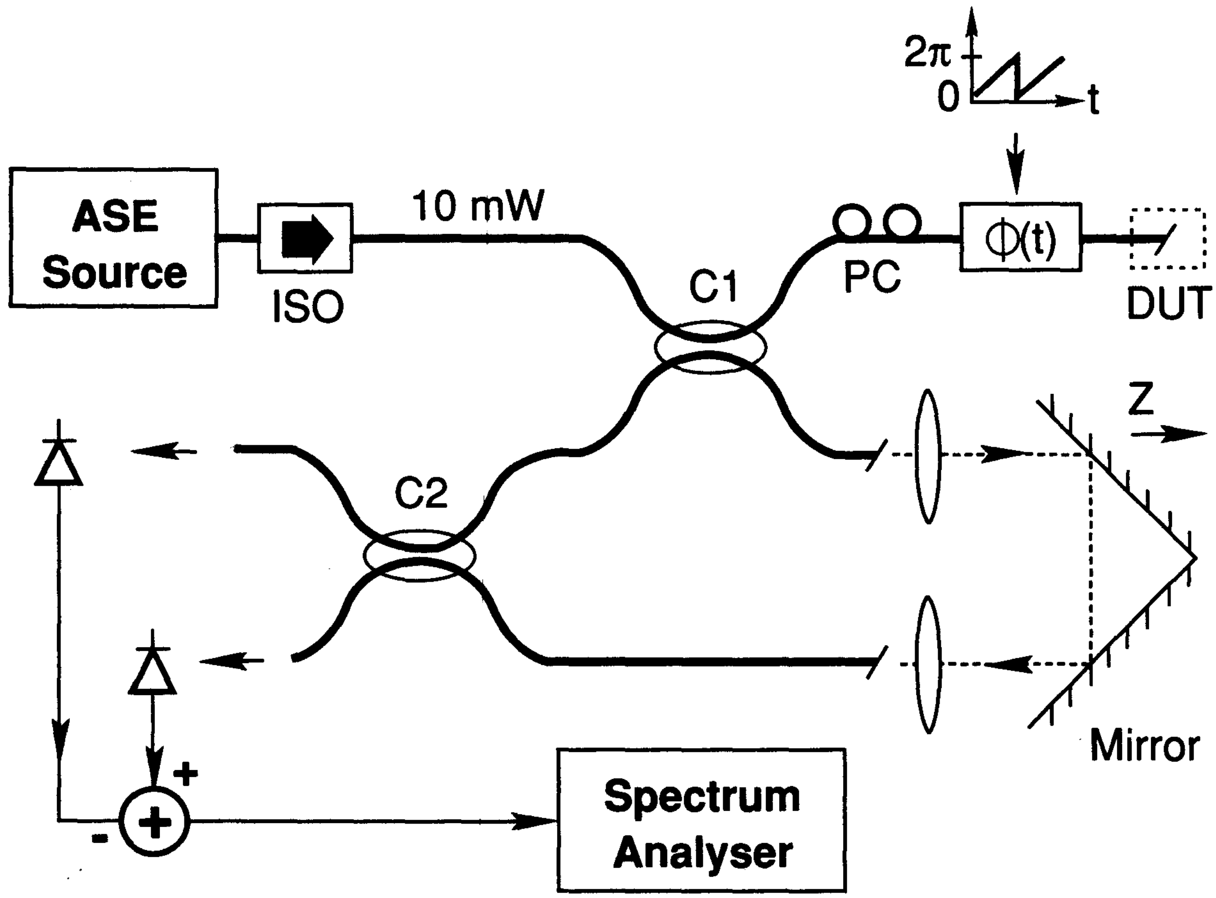
OLCR configuration for the measurement of Rayleigh backscattering.

Figure 2

(a) Unaveraged RBS data with 32 μm spatial resolution. End of angle-cleaved fiber occurs at 76 mm. (b) Spatially averaged RBS data with 3.4 mm resolution.

Figure 3

Averaged RBS signal at a fusion splice between a standard single-mode fiber (SMF) and an erbium-doped amplifier fiber. Spatial resolution is 700 μm.



ASE
Source
ISO
10 mW
C1
PC
2π
0
t
Φ(t)
DUT
Z
C2
Mirror
+
-
Spectrum
Analyser

Figure 1

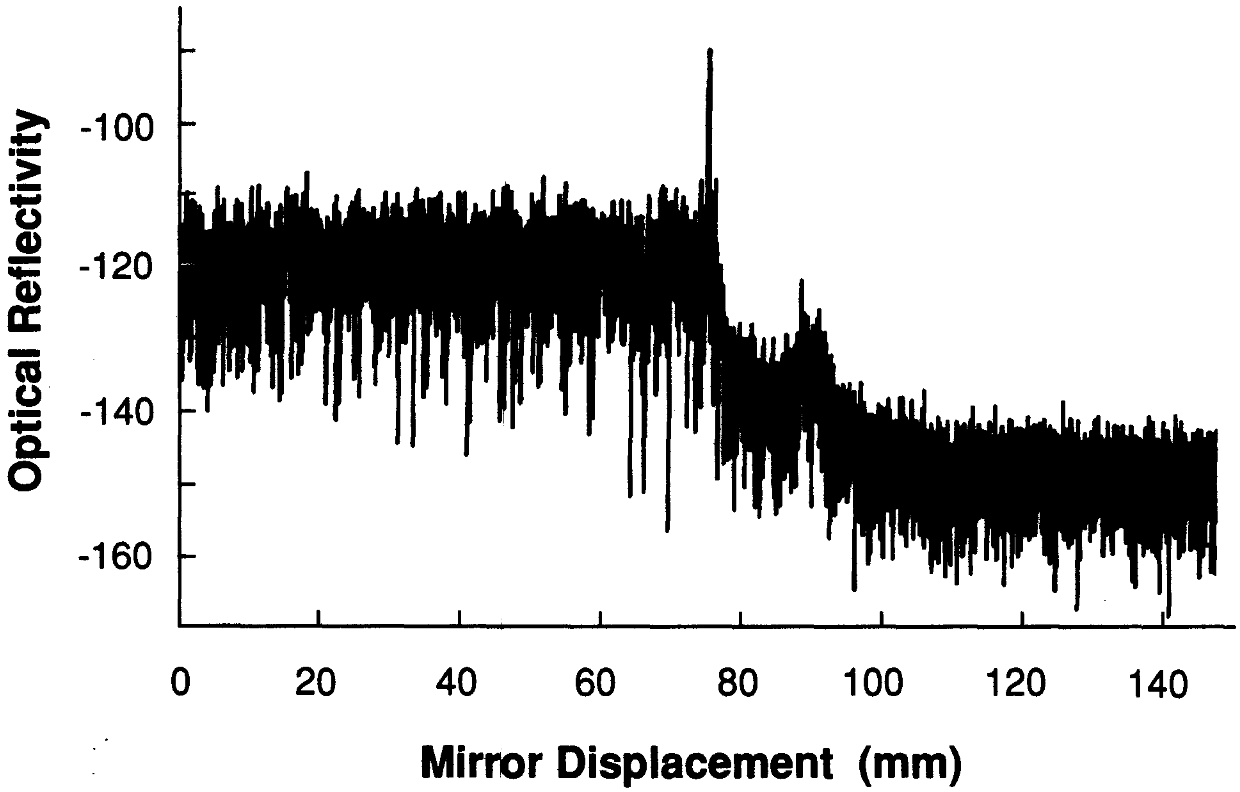

Optical Reflectivity
-100
-120
-140
-160
0
20
40
60
80
100
120
140
Mirror Displacement (mm)

Figure 2a

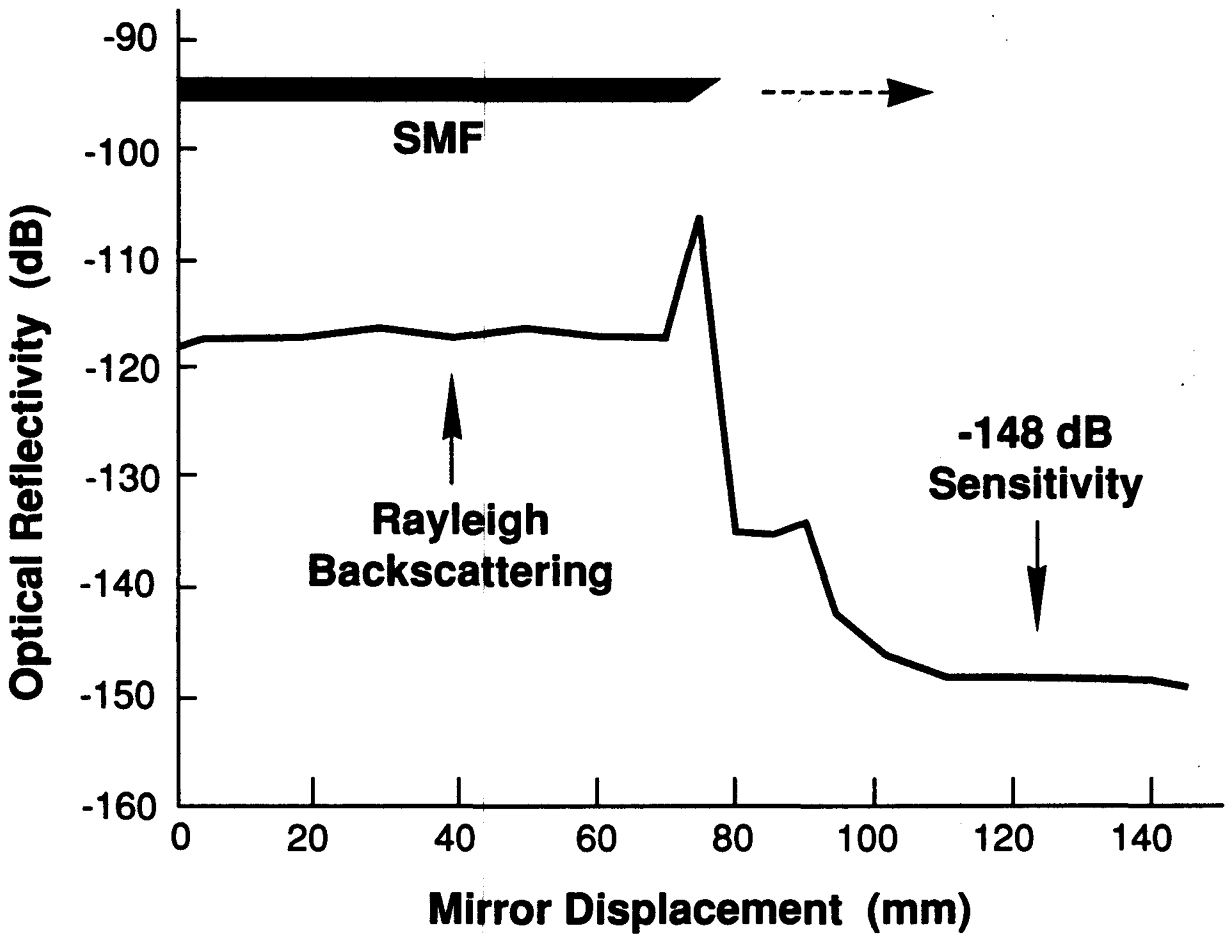
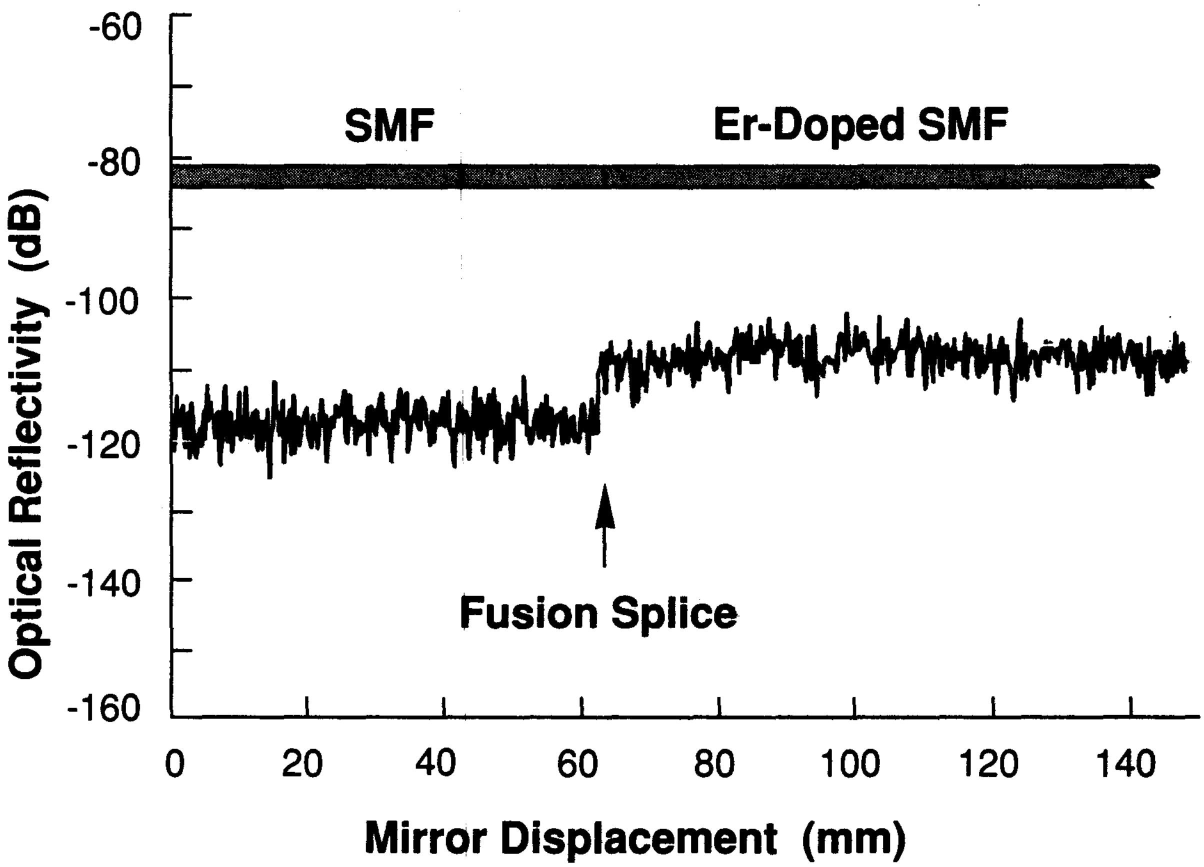

-90
-100
-110
-120
-130
-140
-150
-160
SMF
Rayleigh
Backscattering
-148 dB
Sensitivity
0
20
40
60
80
100
120
140
Optical Reflectivity (dB)
Mirror Displacement (mm)

Figure 2b



-60
-80
-100
-120
-140
-160
SMF
Er-Doped SMF
Fusion Splice
Optical Reflectivity (dB)
0
20
40
60
80
100
120
140
Mirror Displacement (mm)

Figure 3