High-accuracy Brillouin Gain Spectrum Measurements of Single-Mode Fibers

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The importance of the measurements of the Brillouin gain spectrum has been growing in the past few years owing to its potential use for monitoring strains experienced by optical fibers [1] and for distributed temperature sensing [2]. It is classically measured by launching a highly coherent lightwave into a test fiber and by observing the amplification of a weak probe signal propagating in the backward direction [3]. The optical frequency of the probe signal must be stable and tunable to properly scan the Brillouin gain spectrum. This spectrum lies 12-13 GHz below the pump frequency at a wavelength of 1300 nm and has a Lorenzian line shape with a few tens of MHz FWHM. Generally two different laser sources are used to generate pump and probe signals, although a method using a single laser source, based on spoontaneous Brillouin scattered light analysis has been demonstrated [4]. Frequency resolution better than 1 MHz is difficult to achieve using all these methods, so that highly accurate measurements are not available so far. Especially only rough estimates for the FWHM linewidth (40-70 MHz) and the peak gain (1.5-2.5×10^{-11} m/W) have been reported to date [3, 4, 5].

In this contribution, we present a novel method using a single laser source for BGS measurements and the pump-probe technique. It makes possible reference measurements owing to its ideal inherent frequency stability and excellent SNR. Systematic measurements of fibers having various core-cladding index differences were performed, leaving accurate values for Brillouin gain parameters. A general behavior was observed and relations between Brillouin gain spectrum parameters and fiber core-cladding index difference are confirmed [4].
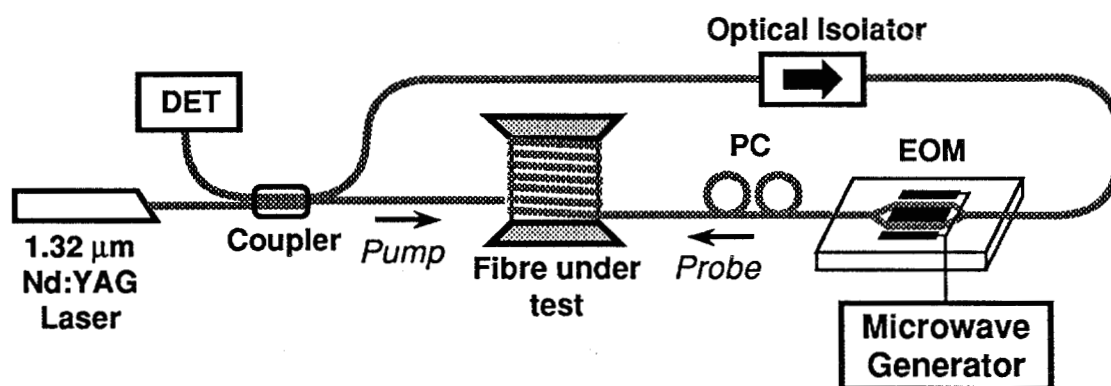

Fig. 1. Experimental setup for Brillouin gain spectrum measurements

The experimental setup is schematically shown in Fig. 1 [6]. Pump and probe signals originate in the same 1.32 µm Nd:YAG laser and are launched into the test fiber in opposite directions using a coupler. The isolator blocks the pump light, so that only the probe signal illuminates the detector. The test signal

is set at the proper frequency by modulating the laser light using an ultrawideband electro-optic modulator driven by a synthetised signal generator. This creates two sidebands in the optical spectrum that are separated from the pump frequency by the modulation frequency. When this frequency corresponds to the Stokes shift, Brillouin interaction may occur. The lower sideband experiences gain and grows exponentially as it propagates along the fiber under test, whereas the upper sideband is depleted and decays exponentially. The sum of this two effects yields an hyperbolic cosine relationship between amplification and gain coefficient.

$$I(L) = 2\, I_o\, \cosh\{\, g_B(v)\, I_p\, L_{eff}\}$$

where I_o is the test signal input intensity, g_B is the Brillouin gain coefficient, I_p is the pump intensity and L_{eff} is the usual effective fiber length for the nonlinear interactions. This relationship is only strictly valid under the assumption that any effect on the pump signal (gain or depletion) is negligible.
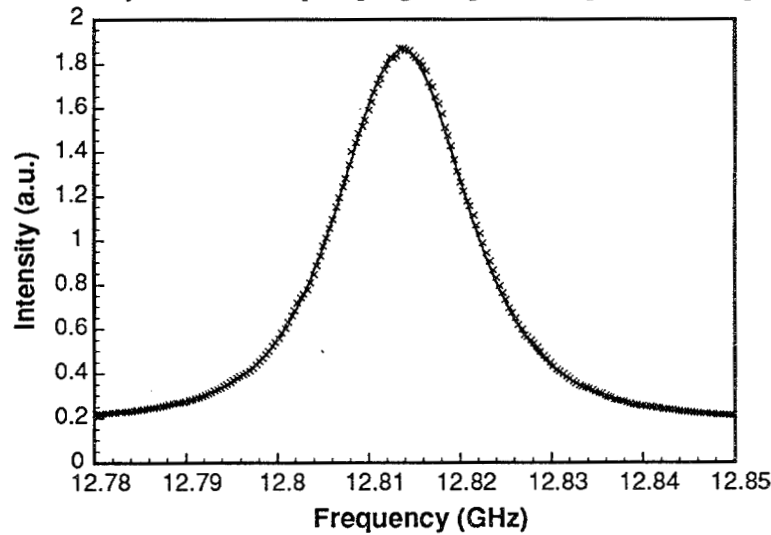

Fig. 2. Measured Brillouin amplification spectrum of a standard single mode fiber ($\Delta n = 5 \cdot 10^{-3}$, core diameter 9μm). Solid line is the numerical fit of the theoretical curve (hyperbolic cosine of a Lorentzian function).

A typical Brillouin gain spectrum measured using this method is shown in Fig. 2. The measured gain curve $g_B(v)$ perfectly fits a Lorentzian function and the Brillouin parameters can therefore be acurately determined. The length of the different measured fibers was in the 100m-600m range and were wound by hand to avoid any tension. Regular mechanical winding induces stresses that were observed to bias the measurements by causing an inhomogeneous broadening of the gain curve. Care was also taken to decrease the test signal amplitude until no effect on the gain curve are measured, meaning a negligible pump depletion.

Table I summarizes the measurements performed on theses fibers. The Brillouin Stokes shifts range from 11.5 GHz to 12.8 GHz and a clear relationship is observed between Stokes shift and core-cladding index differences, as shown in Fig. 3., confirming previously reported results [4]. An interesting feature is the excellent agreement between the extrapolated value for $\Delta n = 0$ and the Stokes shift calculated for bulk silica.

Another relationship was found between Stokes shift v_B and Brillouin gain line width, as shown in Fig. 4. The extrapolated value for $\Delta n = 0$ is close to the bulk silica value, but the agreement is not perfect. This may be due to excess phonon damping occurring in the fiber waveguide, though the confidence level of the measurements made in bulk silica is not known. These measurements provide with a high

Core-cladding Δn ($\times 10^{-3}$)	Brillouin shift (GHz)	Linewidth (MHz)	Spot size μm	Peak Gain g_0 m/W	Power Gain g_0/A_{eff} m^{-1} W^{-1}
Bulk Silica	13.1000	23.0			
4.5	12.8527	34.5	5.04		
5.0	12.7960	35.7	4.64	$1.59\ 10^{-11}$	0.23
5.0	12.8088	35.4	4.82	$2.02\ 10^{-11}$	0.28
8.0	12.7191	34.5			
10.5	12.3886	40.6			
14.0	12.3309	42.5	2.96	$1.42\ 10^{-11}$	0.52
30.0	11.5094	52.4	1.84	$1.91\ 10^{-11}$	1.79

Table I. Summary of measurements performed on different fibers, together with aome fibers characteristics and calculated gain. Values for bulk silica are extrapolated from reported measurements.

confidence level a 35 MHz value for the Brillouin FWHM linewidth of standard telecommunication fibers ($\Delta n=5 \cdot 10^{-3}$) at 1.32 μm.

Finally the Brillouin gain coefficient g_0 was calculated from the maximum of the BGS after measurement of pump power and spot size ω_0. The effective cross section A_{eff} was determined using the classical formula $A_{eff}=\pi\omega_0^2$. A quite important fluctuation in the gain evaluation (1.4-2 10^{11} m/W) is observed but there is no clear correlation between gain value and core doping. This confirms the assumption that Brillouin interaction predominantly takes place within the core, so that the effective cross section A_{eff} must be weighted by the overlap integral between mode field distribution and core index profile [4]. Actually the highest gain is obtained for a fiber with no dip and a very uniform core index distribution, and lowest gain for a triangular profile. Care was taken to carefully adjust pump and probe
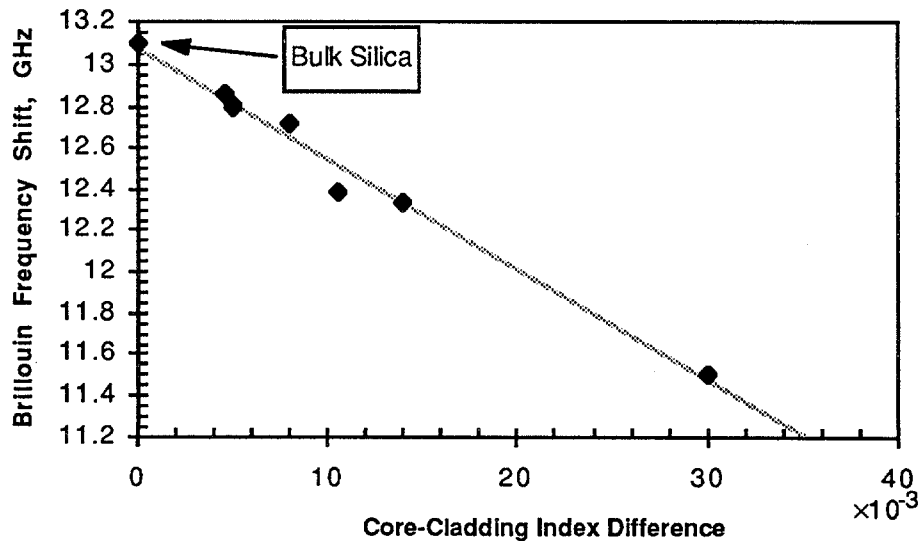

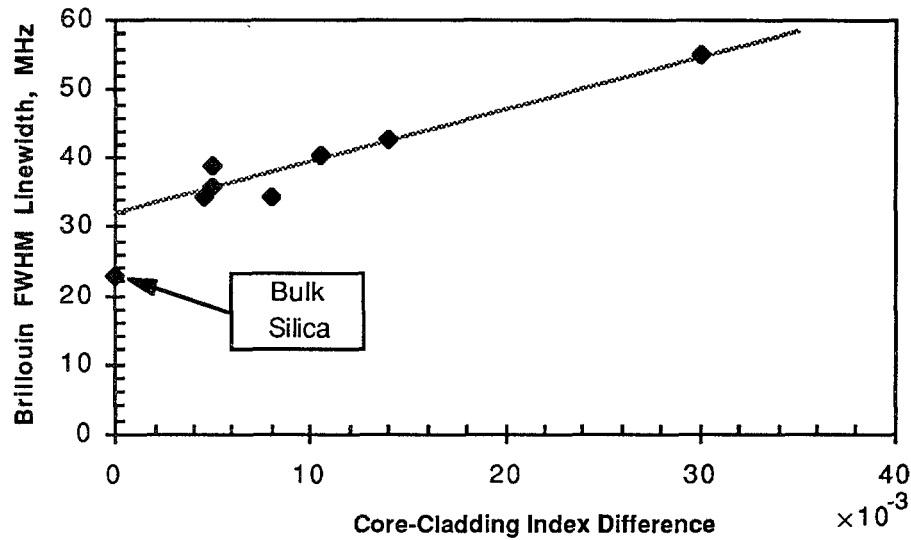*Fig. 3. Relationship between the frequency of the Stokes shift and the core-cladding index differences*

Fig. 4. Relationship between Brillouin gain linewidth and the core-cladding index difference.

polarizations, so that polarization scrambling effects are made negligible. This was checked by observing the absence of amplification in the orthogonal state of polarization.

The difficulty to exactly determine the effective cross section A_{eff} makes the power gain coefficient g_0/A_{eff}, shown in Table I, more suitable for fiber characterisation. Overall amplification can be calculated directly from pump power and comparative measurements are possible without further calculations using additional parameters (spot size, index profile).

In conclusion highly accurate measurements of the Brillouin gain curve were performed in fibers with very different guiding characteristics. These measurements explain the differences observed between fibers and bulk silica and the scattered value reported by different authors. They also confirmed that the core doping decreases the acoustic velocity - and thus the Stokes shift - and the phonon lifetime, causing a broader linewidth, and has a negligible effect on the gain coefficient.

Acknowledgments

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