1120

LANDAU PLACZEK RATIO
APPLIED TO DISTRIBUTED FIBRE SENSING

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Abstract

It is shown experimentally that the ratio of the intensities of Rayleigh and Brillouin backscattered light (Landau Placzek ratio) in an optical fibre has a temperature dependence which may be used for the basis of a distributed temperature sensor. This result, combined with the known frequency dependence of the Brillouin backscattering on temperature and strain, indicates that spontaneous Brillouin backscatter may be used for the unique determination of either temperature or strain in a distributed optical fibre sensing system.

1. Introduction

One of the most important advantages to be offered by optical fibre sensors, for which there is no practical counterpart based on competing technology, is that of distributed sensing. True distributed sensing allows the measurement of the measurand at any and every point along the sensor.

The principle of operation of existing backscatter distributed fibre sensing (DFS) systems is similar to that of the optical time domain reflectometer (OTDR) [1]. In the OTDR, a short pulse of light is transmitted along the fibre and the backscattered energy due to Rayleigh scattering is measured at the sending end of the fibre. The time interval between sending the pulse and detection of the backscattered energy provides the spatial information, whilst the intensity of the backscattered energy provides a measure of the fibre attenuation. In Brillouin OTDR (BOTDR) DFS systems, the Rayleigh backscatter mechanism is replaced by Brillouin backscattering. Brillouin scattering [2] occurs in optical fibres [3] and results from the interaction between the incident light beam and thermally generated acoustic waves in the fibre. The frequency of the captured backscattered light is effectively Doppler shifted due to the velocity of the acoustic wave. The frequency shift is a function of both temperature [4] and strain [5] in the fibre. Hence, the measurement of the frequency of the backscattered light provides a measure of the combined effects of strain and temperature along the fibre.

The main advantage of Brillouin backscatter over Raman backscatter DFS systems [6], is that standard telecommunications single mode fibre may be used to measure both temperature and strain. Furthermore, although the temperature sensitivity of the Brillouin backscattered signal is roughly $0.3\%K^{-1}$, compared to the Raman sensitivity of $0.8\%K^{-1}$, the intensity of Brillouin backscattered light is an order of magnitude greater than Raman scattering, which is already used in commercial instruments [7]. This promises potentially greater temperature resolution and, or, distances than existing systems.

It has been stated that the frequency shift between the incident light and the Brillouin backscattered light is a function of temperature and strain. This therefore provides a means of measuring both temperature and strain. However, if only the frequency shift is measured and the sensor is subjected to simultaneous changes in temperature and strain, there is no way of uniquely measuring each unless their effects can be separated [8].

The results presented here, show how the change in Brillouin backscatter intensity may be used to uniquely determine temperature in a DFS. This measurement may then, in conjunction with a measurement of frequency shift, be used to unambiguously determine the strain along the DFS.

One problem of intensity based sensors is identifying whether the changes in intensity are due to changes in the measurand or due to some other cause of fibre attenuation such as splice loss or microbending. Fortunately, the Rayleigh backscatter signal, which is insensitive to temperature changes, provides a means of measuring the fibre attenuation due to these other causes. Owing to the relatively small frequency difference between the Brillouin shifted signal and the Rayleigh backscattered signal, the fibre attenuation will be the same for both signals. Hence the ratio of the Rayleigh and Brillouin backscattered intensity, known as the Landau Placzek ratio (LPR), provides a means of measuring the temperature along the DFS.

2. Theoretical

The ratio of the integrated intensities of the central Rayleigh component (I_R) and the sum of the two Brillouin components (I_B) was first investigated by Landau and Placzek [9]. They found that for a liquid:

$$\frac{I_R}{I_B} = \frac{c_p - c_v}{c_v} \tag{1}$$

where c_p and c_v are the specific heats at constant pressure and constant volume, respectively. Hence, equation (1) is known as the Landau Placzek formula and I_R/I_B is the Landau Placzek ratio.

Schroeder et al [10] have shown that for a single component glass, the LPR is given by:

$$R_{LP} = \frac{I_R}{I_B} = \frac{T_f}{T}(\rho_o v^2 \beta_T - 1) \tag{2}$$

where ρ_o is the density, v is the acoustic velocity, β_T is the isothermal compressibility of the melt at the fictive temperature (T_f) and T is the temperature. The fictive temperature is the temperature at which the thermodynamic density fluctuations in the melt are frozen into the glass. Equation (2) indicates that the LPR has a reciprocal temperature dependence.

For a multicomponent glass equation (2) must be modified to account for local fluctuations in composition. Schroeder et al show that for a binary system, an additional term representing the scattering due to composition fluctuations must be added:

$$R_{LP} = \frac{I_R^\rho + I_R^c}{I_B} = R_\rho + R_c \tag{3}$$

where I_R^ρ is the original scattering due to density fluctuations and I_R^c is the scattering due to the additional composition fluctuations. For a more complete description the reader is refered to Schroeder's paper.

However, the main point to note is that the reciprocal dependence of the LPR with temperature is maintained.

The change in density with temperature is extremely small and is neglected. The velocity of the acoustic wave is given by [11]:

$$v = \sqrt{\frac{E(1-\mu)}{(1+\mu)(1-2\mu)\rho}} \tag{4}$$

where E is Young's modulus and μ is Poissons ratio. Both of these terms are dependent on temperature and hence, so is the acoustic velocity, with a small but positive temperature coefficient. However, the reciprocal temperature term of the LPR is the dominant term yielding the temperature dependence and this is shown in figure 1, using data from Bansal and Doremus [12].

3. Experimental

The experimental set up is shown in figure 2. The source was a distributed feedback laser (DFB) providing approximately 0.9mW at 1537nm. In order to suppress the generation of stimulated Brillouin scattering along the DFS, the injection current of the DFB was modulated to broaden its effective linewidth. A triangular wave of 3mA pk-pk at a frequency of 0.6MHz was used. This produced a source 'linewidth' of approximately 2GHz. The acousto optic modulator (AOM) was a fibre pigtailed device with an insertion loss of 4.5dB and a rise time of 44ns. The AOM was gated to produce pulses of 6μs with a period of 160μs. The output from the AOM was amplified by the erbium doped fibre amplifier (EDFA) which produced a pulse power of 18dBm. This was coupled to the sensing fibre by a 50% coupler C2, to maximise the backscattered signal.

The sensing fibre consisted of three lengths each of 4.3km, 125μm telecommunications grade fibre with a specified cutoff of 1180-1280nm and attenuation of <0.22dB/km. The centre section was placed in an oven and maintained at a temperature of 55°C.

The backscatter signal was extracted from the sensing fibre via C2 and the fibre output collimated and directed through the scanning Fabry Perot (FP) which was used to separate the Rayleigh and Brillouin components. The FP was set to a free spectral range of 50GHz with a finesse of 100 and a transmission loss of approximately 10dB. The output from the FP was focused onto a 300μm InGaAs detector connected to a 100MΩ transimpedance amplifier with a bandwidth of 175kHz. A 3nm band pass filter was used in front of the detector to attenuate the Rayleigh backscatter from the interpulse EDFA amplified spontaneous emission. The Rayleigh and Brillouin traces were stored separately on a digital storage oscilloscope using 2048 averages and the LPR determined from $P_R/(2P_{AS})$ where P_R and P_{AS} are the measured backscatter Rayleigh and anti-Stokes powers respectively.

4. Results

In order to establish a baseline of known attenuation characteristics of the sensing fibre, a measurement was made using a commercial OTDR (Anritsu model no: MW98A). This is shown in figure 3. The first splice between the first and second sections of fibre has no measurable loss. The second splice between the second and third sections of fibre has a measured loss of 0.2dB.

The backscatter spectrum from the sensing fibre is shown in figure 4. The relative powers of the Stokes and anti-Stokes signals were observed to ensure that stimulated Brillouin was completely suppressed; as only the Stokes component (lower frequency) is subject to stimulated scattering, its suppression is indicated when the two Brillouin components are equal in power.

The Rayleigh and anti-Stokes components of the backscattered signal were separated by manually controlling the bias to the FP. These are shown in figures 5(a)&(b) respectively.

It can be seen that the Rayleigh backscatter trace suffers from a low frequency noise component with a particularly strong disturbance at about 24μs approaching 3%. There is no indication of splice loss between the first and second sections of fibre. However, the second splice between the second and third sections can be seen at about 85μs. The signal attenuation at this point, estimated from the trace, is 0.91 corresponding to 0.4dB. This represents a one way splice loss of 0.2dB.

The anti-Stokes trace does not possess the low frequency noise of the Raleigh backscatter signal, but does suffer from a higher level of broad band noise from the detector. It is seen that the backscatter from the second section of fibre, heated to 55°C in the oven, increased in power by a factor of 1.12, corresponding to 0.5dB. The backscatter from the third section was attenuated by 0.81 or about 0.9dB.

The LPR is shown in figure 5(c). For the first section of fibre at an ambient temperature of 21°C, the LPR is 31.7. This drops to 28.6 for the second section of fibre at the oven temperature of 55°C. The ratio of the third section is approximately 31.6.

It should be noted that the LPR as determined in this experiment is a slight over estimation of the true value. The reason for this is that the source bandwidth ($\approx$2GHz) is somewhat larger than the FP bandwidth ($\approx$500MHz). The backscattered Brillouin component will have a bandwidth equal to the convolution of the source and Brillouin backscatter mechanism. Hence the Brillouin component will have a lower proportional power spectral density than the Rayleigh component. This will result in the measured LPR being more than the predicted value. However, this error is estimated to be less than 0.1%. Furthermore, this is of no consequence in this experiment, as it is the ratio of the LPR, not the absolute LPR, that is being used to determine the temperature change relative to the known ambient temperature. For absolute measurement of temperature, a knowledge of the other parameters of equation (2) are required.

The main source of noise on the LPR trace is due to the low frequency noise component on the Rayleigh backscatter signal previously mentioned and 3% disturbance results in a potential error of 10°C.

5. Discussion

It is not possible to determine the temperature implicitly from the measurement of the LPR unless all of the terms constituting equation (2) are known. Furthermore, for a multicomponent glass, detailed knowledge of the glass composition would be necessary. However, provided a single calibration LPR measurement is made at a known temperature, then the temperature along the fibre may be determined from the ratio of the measured LPR to the calibration LPR; the temperature ratio being the inverse of the LPR ratio.

From the data of figure 1, the expected change in the LPR between the ambient temperature of 21°C and the oven temperature of 55°C is 9.2%. The change in the measured value of LPR between the first (31.7) and second (28.6) section of fibre, is 9.8%. There is therefore good agreement between the measured and expected values.

The splice loss measured by the DFS (0.2dB) agrees with that of the OTDR. The LPR of the third section of fibre (31.6) differs from the first (31.7) by 0.3%. It is therefore concluded that this ratio method has adequately compensated for the splice loss existing in the sensing fibre.

The aim of this experiment was to demonstrate the principle of using the LPR for the purpose of DFS. The pulse width used in this experiment was 6μs giving a spatial resolution of 600m over the 12.9km length. This pulse width was arrived at as a compromise between sensitivity and bandwidth of readily available detectors and pulse power consistent with suppression of both stimulated Brillouin scattering and interpulse amplified spontaneous emission from the EDFA. Previous experimental results [13] show that the spontaneous Brillouin linewidth is well in excess of 20MHz which would allow a pulse length shorter than 16ns to be used, giving a spatial resolution approaching 1m.

It is considered that a system utilising this mechanism would have greatest potential, when used to compensate for temperature changes in a distributed strain sensing system. In fact, many applications of distributed strain sensing involve systems with large thermal masses and slowly varying temperature distribution both spatially and temporally. Nevertheless, considerable improvement is possible regarding the spatial resolution provided detectors with lower noise and high speed are used.

It is seen from figure 5(c) that the signal/noise ratio of the measured temperature would result in a potential error larger than could be tolerated in a practical system, the standard deviation being 0.6. The main reason for this is the low frequency perturbations on the Rayleigh backscatter trace of figure 5(a), which are due to the coherent nature of Rayleigh scattering resulting in interference on the detector between light from different parts of the fibre. These are not present on the Brillouin trace as the random nature of the Brillouin process results in only a short term coherence. Nor are they present on the OTDR trace as the instrument uses a pulsed LED with a broad spectral output of about 35nm. Higher optical powers would not improve the S/N due to this cause. Furthermore, higher powers would bring about stimulated Brillouin scattering (SBS), although the SBS threshold would be increased by using shorter pulse lengths which would be necessary for improved spatial resolution.

In the light of the foregoing, there is considerable scope for improvement not only in the spatial resolution but also in the signal/noise ratio regarding both the low and high frequency noise.

An improvement in low frequency signal/noise could be achieved by using a broad band source to derive the Rayleigh reference signal. Alternative schemes to broaden the light source linewidth to alleviate the problem are the subject of our future investigations.

The high frequency noise is mainly due to the transimpedance amplifier after the detector. The effects of this could be reduced by increasing the backscatter signal at the detector without inducing SBS, by using a coupler (C2) with a ratio of say 5/95% instead of 50/50%. As the fundamental power limit is determined by the SBS threshold, the output from the EDFA would be increased ten fold resulting in the same optical power in the sensing fibre. In the backscatter path this would result in 95% of the backscatter power being coupled out of the sensing fibre instead of the current 50%; a potential improvement approaching 2.8dB.

In theory, it should be possible to surpass the temperature resolution demonstrated by existing distributed temperature sensing systems based on Raman scattering, as the Brillouin signal is approximately one order of magnitude larger than the Raman signal. Although this would be partially offset by the reduced temperature sensitivity.

The sections of fibre were loosely wound on the fibre drums to alleviate the effects of temperature on strain and microbending. Measurements of the effect of strain on the LPR have not been made to date but are the subject of future work.

Using data from the Handbook of Glass Properties [12], equation (2) gives a value of 2000K for T_f. This is a rather coarse estimation as equation (2) is for a single component glass. However, it compares with the fibre pulling temperature of approximately 2300K.

6. Conclusion

It has been demonstrated that the Rayleigh/spontaneous Brillouin ratio (Landau Placzek ratio) may be used as a temperature sensing mechanism in a distributed fibre sensing system. Theoretical indications are that it is largely unaffected by strain and may therefore be used in conjunction with Brillouin frequency shift measurements to uniquely determine both temperature and strain in a distributed fibre optic sensing system. Owing to the close proximity of the Rayleigh and Brillouin backscatter frequencies, taking their ratio has shown to provide good compensation for splice and fibre losses and avoids the necessary complication of measuring fibre attenuation at both the pump and shifted frequencies in existing distributed temperature sensing systems based on Raman scattering.

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Figure captions:

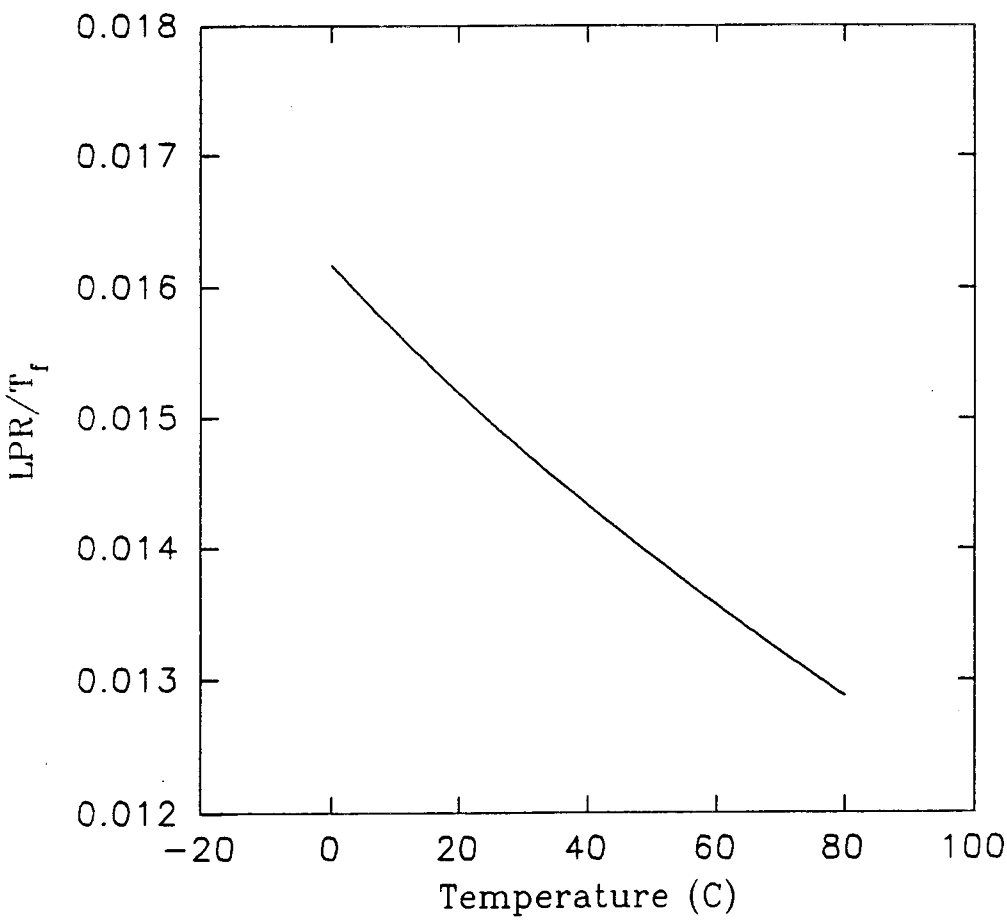
Figure 1 Variation of Landau Placzek ratio/fictive temperature with temperature.

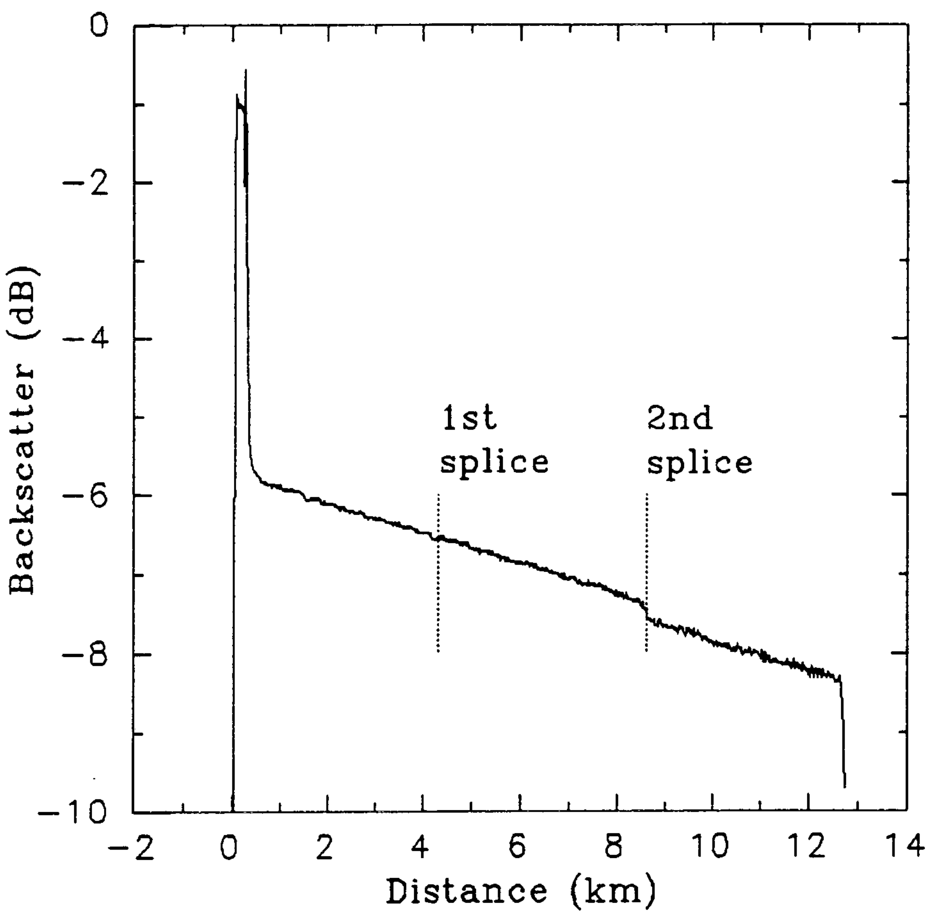
Figure 2 Experimental schematic.

Figure 3 Backscatter from sensing fibre using a commercial OTDR. Pulse length = 2μs.

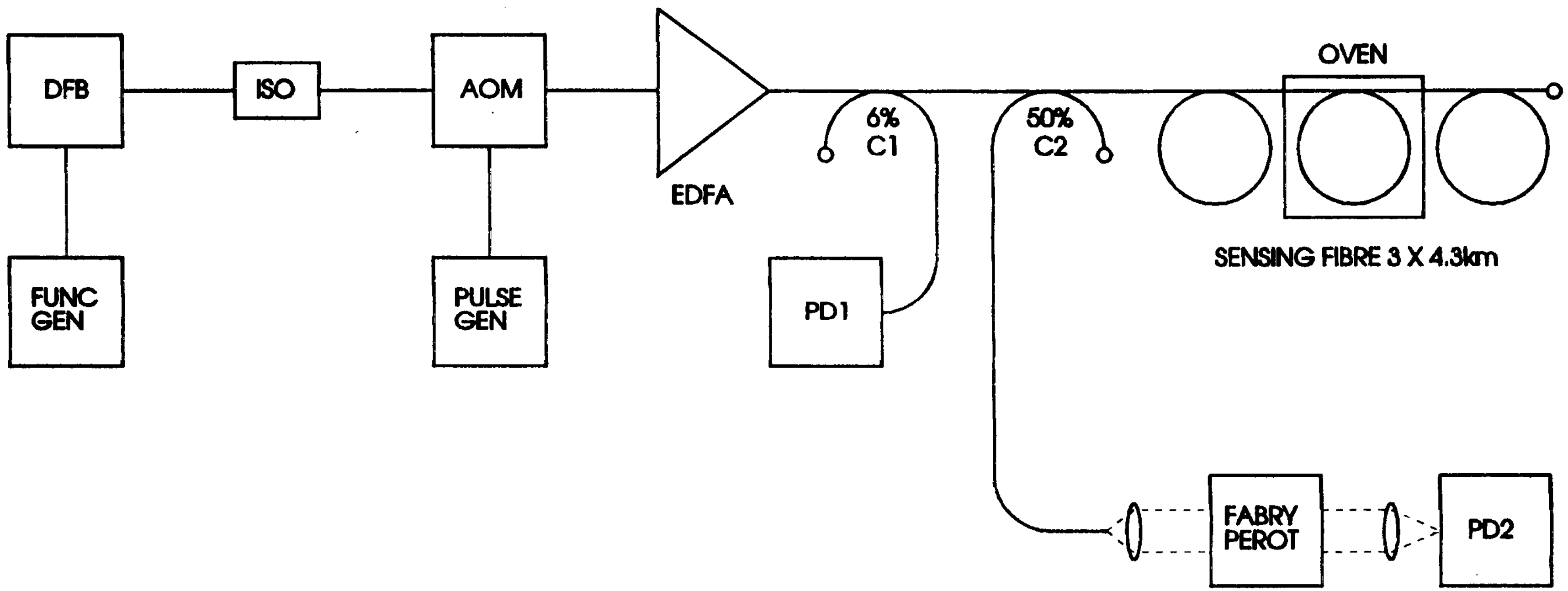
Figure 4 Spectrum of backscattered light showing relative powers of Rayleigh, Stokes and anti-Stokes. FSR = 50GHz.

Figure 5 Backscatter from sensing fibre and LPR.

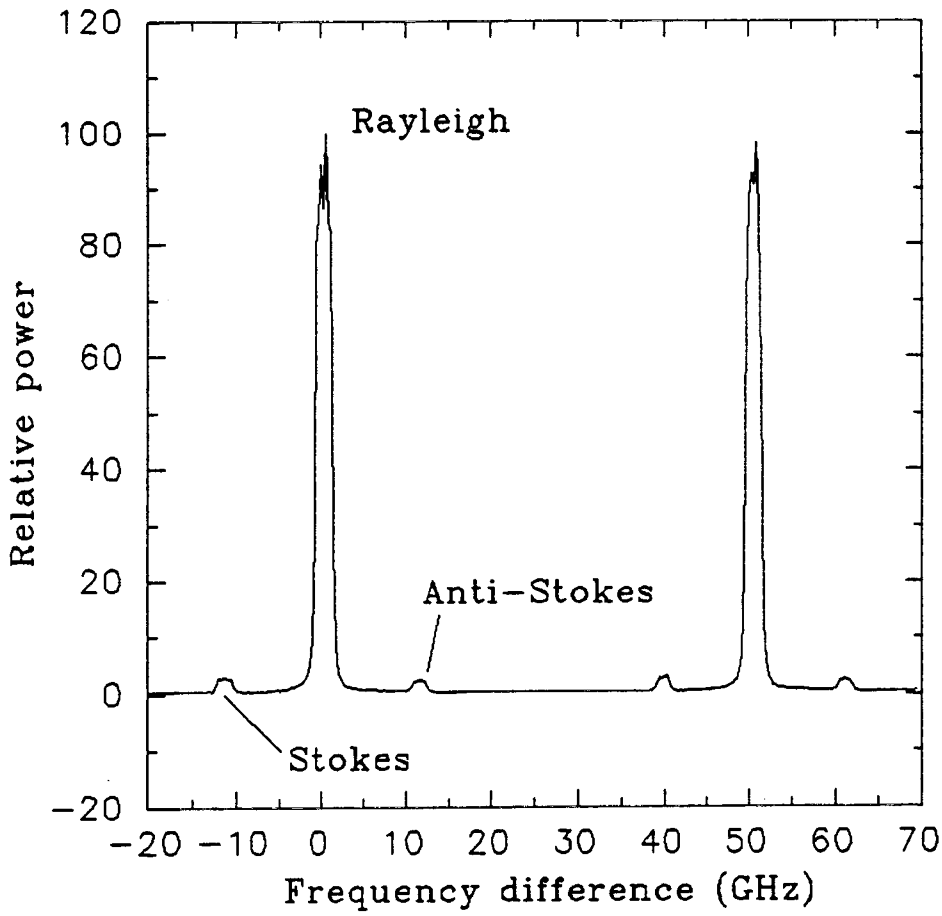

0.018
0.017
0.016
0.015
0.014
0.013
0.012
LPR/T_f
−20
0
20
40
60
80
100
Temperature (C)



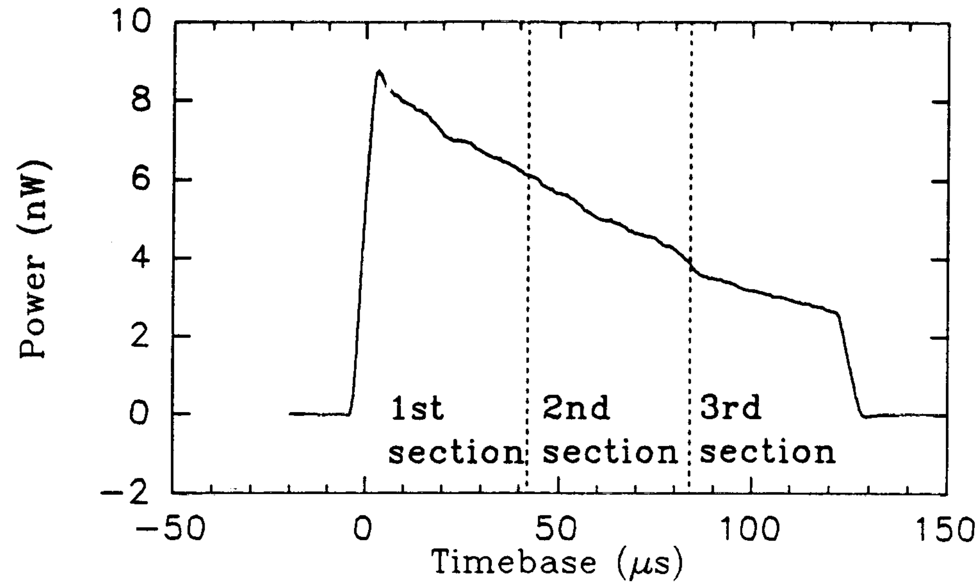
Backscatter (dB)
0
−2
−4
−6
−8
−10
−2
0
2
4
6
8
10
12
14
Distance (km)
1st
splice
2nd
splice



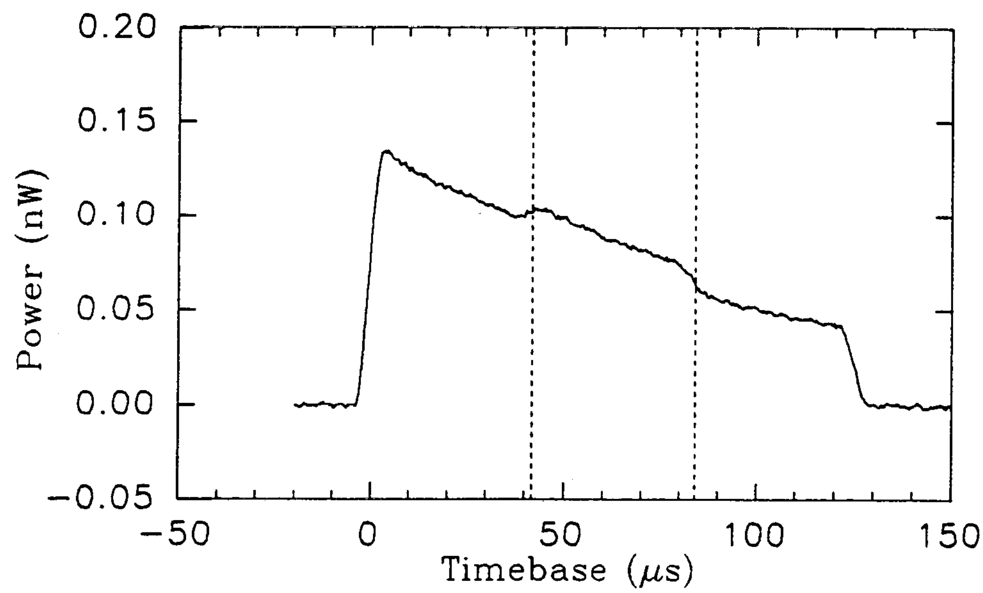
DFB
ISO
AOM
EDFA
6%
C1
50%
C2
OVEN
FUNC GEN
PULSE GEN
PD1
SENSING FIBRE 3 X 4.3km
FABRY PEROT
PD2



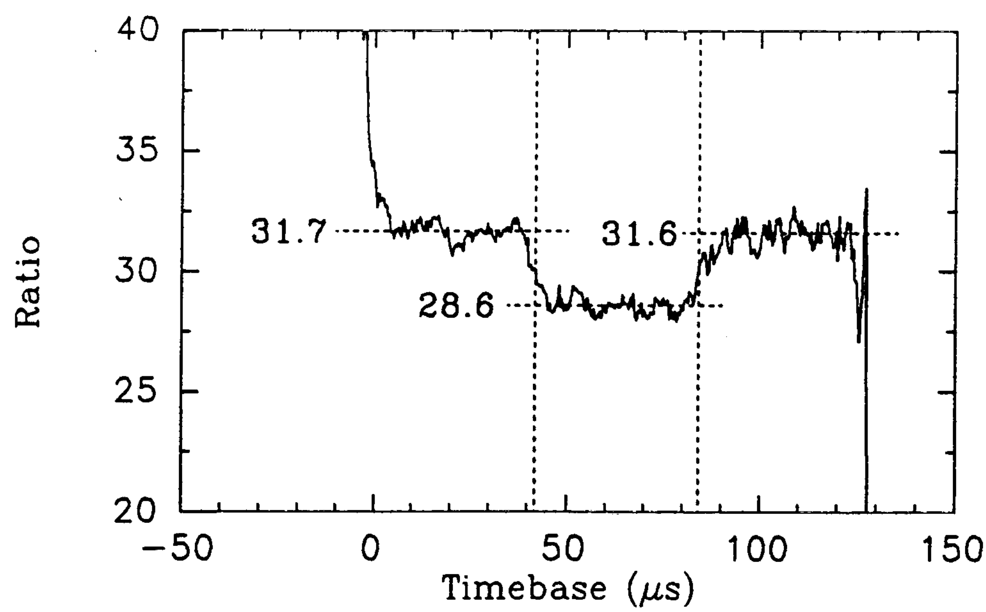
Rayleigh
Anti-Stokes
Stokes
Relative power
Frequency difference (GHz)
120
100
80
60
40
20
0
−20
−20
−10
0
10
20
30
40
50
60
70



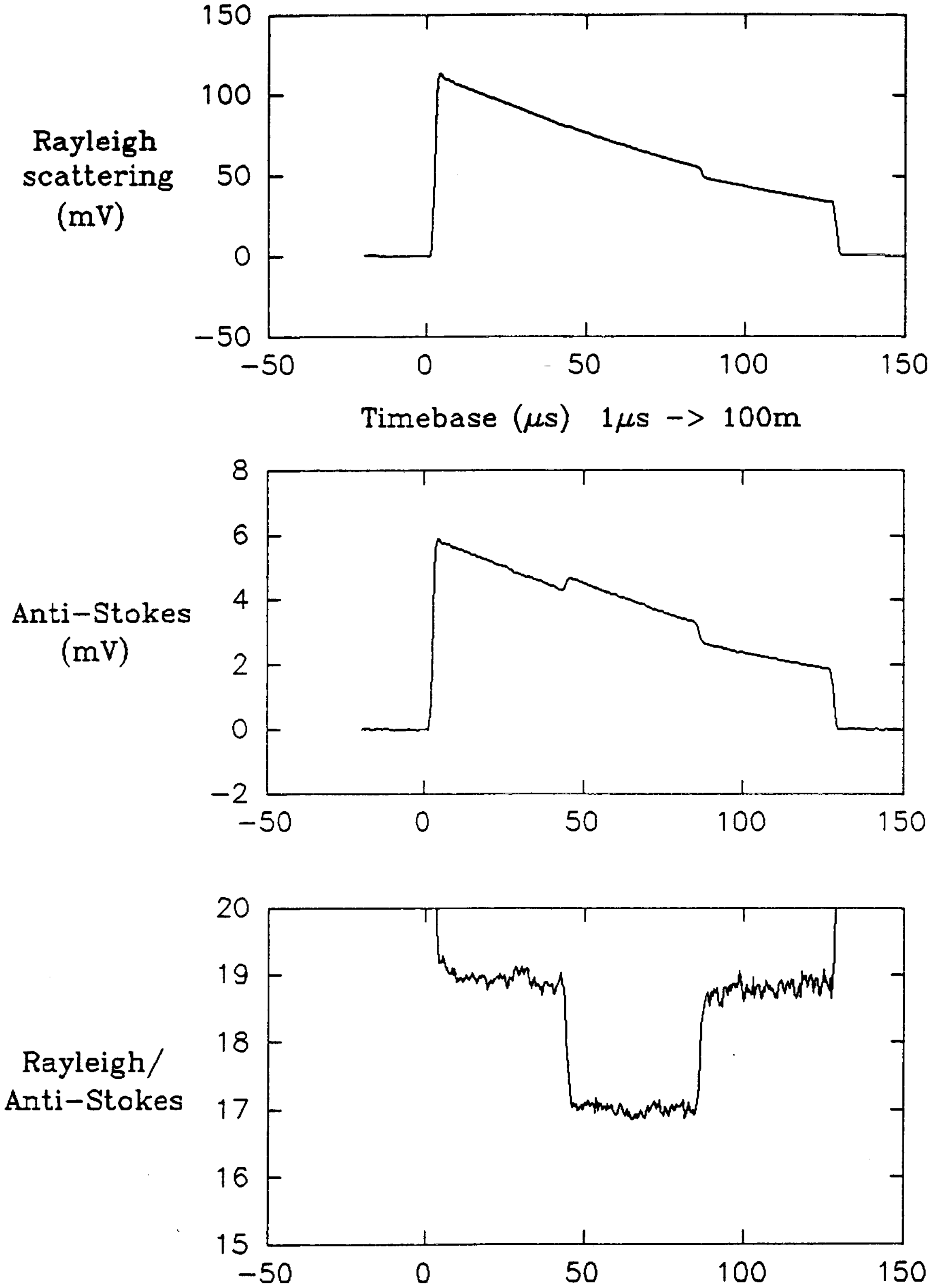
(a) Backscattered Rayleigh



(b) Backscatterd Brillouin anti-Stokes



(c) Measured Landau Placzek Ratio



Rayleigh/Anti−Stokes. Pulse 1.3μs −> spatial resolution 130m
Rayleigh signal obtained from EDFA ASE
Pulse power to FUT: Rayleigh 5.2mW, AS 200mW
Oven temp 60 −> fibre temp 55
DFB 60mA Mod 2MHz 60mVp−p triangle
FP FSR 60GHz

B090116 + B090120
FILE: B090601.SPG