of leakage currents. Note that this current division principle is insensitive to the linearity and hysteresis of the hold capacitors.

**Table 1** TRANSIENT VALUES OF $I_1$, $I_2$, $I_3$ AND $I_m$ (mA) DURING PHASE 1 FOR INPUT CURRENT $I = 2\,\text{mA}$

| $J$ | $I_1[j, 1]$ | $I_2[j, 1]$ | $I_3[j, 1]$ | $I_m[j, 1]$ |
|---|---|---|---|---|
| 1 | 0 | 0·8976378 | 1·1023622 | 0 |
| 2 | 0·2047244 | 0·8057536 | 0·9895220 | 1·1023622 |
| 3 | 0·1837684 | 0·8151591 | 1·0010726 | 0·9895220 |
| 4 | 0·1859135 | 0·8141963 | 0·9998902 | 1·0010726 |
| 5 | 0·1856939 | 0·8142949 | 1·0000112 | 0·9998902 |
| 6 | 0·1857164 | 0·8142848 | 0·9999988 | 1·0000112 |
| 7 | 0·1857141 | 0·8142858 | 1·0000001 | 0·9999988 |

Basically, the accuracy limitation of this current divider stems from the charge injection effect occurring when the switches are turned off. Since currents used in D/A convertors are constant, there is no speed/accuracy trade-off as encountered in A/D convertors.[2] Therefore, the charge injection effect can be reduced to any desired level by simply increasing the hold capacitors, at the only expense of an increase in the circuit area. Moreover, the current calibration technique of Reference 3 can be used to minimise the charge injection effect for a given value of the hold capacitors.

Since the division principle locks the value $I_1 + I_2$ to $I_3$ (i.e. $I_1 + I_2 = I_3$, $T_1$ and $T_2$ forming a locked-pair of transistors), and the sum of these currents is equal to the current to be divided, it is possible to perform a division by $N$ by using $(N - 1)$ locked-pairs of transistors. Finally, by adding simple circuitry, the proposed current divider can supply during each phase currents equal to $I/N$ and $-I/N$.

*Conclusion:* A new highly accurate current divider has been proposed. The basic cell which performs the current division is very simple. No component matching or laser trimming is required for accurate current divisions.

J. ROBERT *3rd May 1989*
P. DEVAL
G. WEGMANN

*Electronics Laboratory*
*Swiss Federal Institute of Technology, Lausanne (EPFL)*
*CH-1015 Lausanne, Switzerland*

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# POTENTIAL OF STIMULATED BRILLOUIN SCATTERING AS SENSING MECHANISM FOR DISTRIBUTED TEMPERATURE SENSORS

*Indexing terms: Optical fibres, Optical sensors, Nonlinear optics*

It is demonstrated that stimulated Brillouin scattering (SBS) occurring in the core of an optical fibre may be used in the construction of a distributed temperature sensor. Initial experiments with a length of fibre have shown that the sensitivity of the Stokes frequency to temperature is approximately 5·5 MHz/°C and that different Stokes frequencies may be observed according to the temperature distribution along the fibre.

*Introduction:* Distributed fibre-optic temperature sensors have been developed which exploit various mechanisms such as back-scattered Rayleigh scattering in liquid filled fibres,[1] doped fibres,[2] back-scattered spontaneous Raman scattering[3] and stimulated Raman scattering[4] (in this Reference the sensor measured distributed stress rather than temperature). Spontaneous Raman scattering appears to be the most promising technique, despite the fact that the scattering cross-section is relatively small. The effect of this small scattering cross-section is to limit the thermal and spatial resolution obtainable although at the same time requiring relatively long measurement times. In this letter we propose the exploitation of another scattering mechanism, namely stimulated Brillouin scattering, for distributed temperature sensing as the stimulated Brillouin scattering cross-section is several orders of magnitude greater.

Stimulated Brillouin scattering (SBS) occurs for relatively low input powers in monomode optical fibres, as the power density is very high because of the fibre's relatively small core size.[5] For applications such as optical communications SBS is seen as a very deleterious effect as it can limit the maximum optical power transmitted by the fibre and hence decrease the distance between repeaters. SBS can be used to advantage in optical fibres, for example to produce amplification.[6]

Stimulated Brillouin scattering can be described as a 3-wave interaction involving the incident light (the pump), a generated acoustic wave and the scattered light wave (the Stokes line). Classically the pump creates a pressure wave in the medium owing to electrostriction and the resultant variation in density changes the optical susceptibility. Thus the incident wave pumps the acoustic wave which scatters it, and this scattering generates the Stokes wave. This wave is downshifted in frequency by an amount equal to the acoustic frequency $\nu_A$:

$$\nu_A = \frac{2V_A n}{\lambda} \sin \theta \tag{1}$$

where $\theta$ is the angle through which the light is scattered ($\theta = 180°$ in the case of full back-scattering such that $\sin \theta = 1$ in our case), $V_A$ is the velocity of the acoustic wave, $n$ is the refractive index of the fibre core and $\lambda$ is the vacuum wavelength of the incident beam.

In normal spontaneous Brillouin scattering there is both a Stokes and an anti-Stokes line where the modulus of the frequency shift is equal to $\nu_A$. In both cases the frequency of the acoustic wave is a function of temperature. The dominant effect producing this dependence is the change of refractive index with temperature. The change in the velocity of the acoustic wave with temperature amounts to only 7% for the range 20–1620°C.[7] Hence from eqn. 1 with $\sin \theta = 1$, we have

$$\frac{d\nu_A}{dT} = \frac{2}{\lambda}\left[V_A \frac{dn}{dT} + n \frac{dV_A}{dT}\right] \tag{2}$$

Thus the change in shift of the Brillouin line with temperature provides a possible mechanism which can be exploited for a distributed temperature sensor. If SBS is to prove viable, then it is necessary to establish first that a change in frequency shift associated with a change in temperature is measurable, and secondly that separate signals corresponding to different temperature regions along the 'effective length' of the fibre can be simultaneously determined. At greater lengths there is insufficient pump power above threshold to stimulate Brillouin scattering and this can be attributed to light being previously scattered along the fibre's length. The effective length $Z_e$ is given by

$$Z_e = \frac{1 - \exp(-\alpha L)}{\alpha} \tag{3}$$

where $L$ is the length of the fibre and $\alpha$ is the loss per metre.

*Experimental:* The experimental configuration shown schematically in Fig. 1 was used to ascertain the dependence of the Brillouin shift with temperature. The two spools of single-mode fibre, which had different core refractive indices, were initially at room temperature. Light from a single-frequency argon ion laser operating at 514·5 nm was launched, via the beam splitter, simultaneously into both fibres (the Glan Thompson and 1/4 wave plate isolated the laser from optical feedback). The back-scattered stimulated Brillouin signal from the two fibres was transferred to a scanning confocal Fabry–Perot (CFP) with a free spectral range of 2 GHz and the output detected with a *pin* diode. The transmitted pump line from one of the fibre ends was passed into the CFP and was used as a frequency reference. The frequency shifts of the back-scattered Brillouin lines were recorded while the temperature difference applied to the fibres was varied by cooling one spool to 0°C and heating the second to 35°C. Fig. 2 shows typical results. The lower trace illustrates the two Brillouin shifted lines at room temperature as well as the unshifted pump line. The upper trace shows the change in Brillouin shift when a temperature difference is applied to the two fibres. One fibre is heated to 35°C and the second fibre is cooled to 0°C.

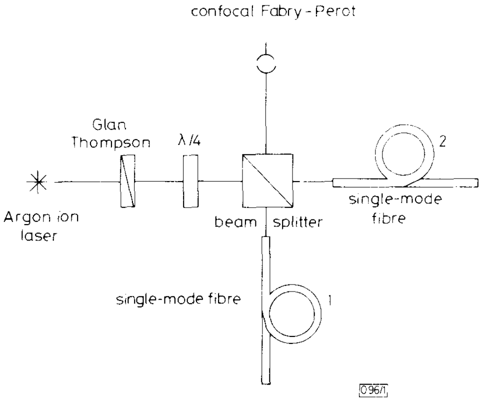

**Fig. 1** *Back-scattered signals from two 500 m spools of single-mode fibre are detected by scanning confocal Fabry–Perot with free spectral range of 2 GHz*

The change in frequency shift of each Brillouin line from the stationary pump line is 2·67 MHz per °C (for fibre 1) when heated to 35°C and 6·4 MHz per °C (for fibre 2) when cooled to 0°C. The difference in shift is accounted for by the difference in refractive indices of the two fibres.

A second experiment was then performed using the arrangement shown in Fig. 3, where only a single fibre (fibre 2) was used. Here, 150 m of the fibre (section A) was cooled to 0°C and the remaining 350 m of the fibre (section B) was heated to 30°C. During this experiment the laser power was adjusted so that both fibre sections are contributing in the scattering process. The results shown in Fig. 4 verify that SBS can occur along a single fibre where the frequency shifts are different and depend on the local value of the fibre temperature. These results are compatible with those of Shibata,[8] where the presence of Brillouin peaks corresponding to different refractive index profiles along the fibre's length are reported.

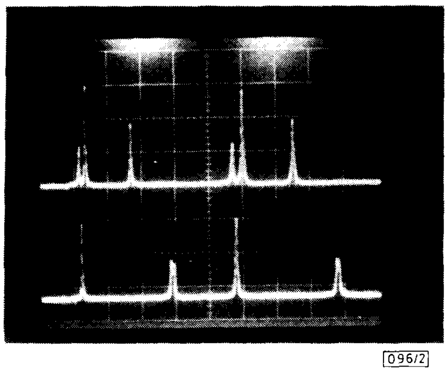

**Fig. 2**

Upper trace: fibre 1 is heated by 11°C and is shown to shift by ≃29 MHz relative to stationary pump line; fibre 2 is cooled to 0°C and shifts to right by 153·6 MHz

Lower trace, scanned over two orders, illustrates two intense Brillouin lines from fibre 1 and two closely spaced pump and Brillouin lines from fibre 2. Pump line is rightmost peak

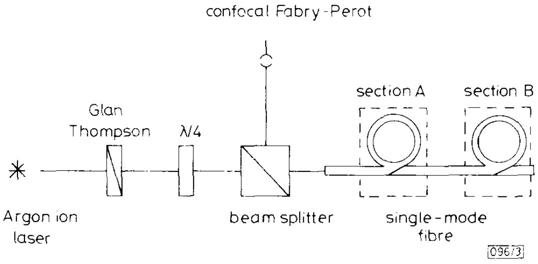

**Fig. 3** *Back-scattered signal is detected by scanning CFP*

The two Brillouin peaks generated by the phonons in the two temperature regions differed in frequency by 171·41 MHz (see Fig. 4). This is equivalent to a shift of 5·7 MHz per °C, which agrees (within the experimental error) to that previously determined.

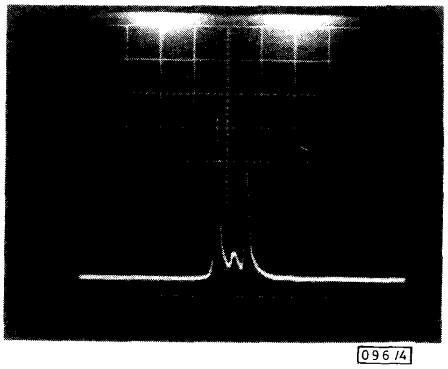

**Fig. 4**

Small central peak is unshifted pump line. Neighbouring peaks, with frequency separation of 171·42 MHz, are Brillouin lines corresponding to sections A and B maintained at 0°C and 30°C

*Summary:* We have demonstrated that SBS signals can be generated along a common length of single-mode fibre where the Brillouin frequency shifts correspond to the temperature of specific sections of the fibre. Hence it should be possible to exploit SBS for distributed temperature measurement. As it is necessary to measure the frequency shift with relatively high precision, the signal processing necessary for this approach to distributed temperature sensing will be more complex than, for example, current systems based upon the Raman effect. However, the significantly higher scattering cross-section should more than compensate for this complexity: experiments are presently in progress based on pulsed laser diodes to evaluate the spatial resolution obtainable by this technique.

D. CULVERHOUSE
F. FARAHI
C. N. PANNELL
D. A. JACKSON

*Physics Laboratory*
*University of Kent at Canterbury*
*Canterbury, Kent CT2 7NR, United Kingdom*

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# STIMULATED BRILLOUIN SCATTERING: A MEANS TO REALISE TUNABLE MICROWAVE GENERATOR OR DISTRIBUTED TEMPERATURE SENSOR

*Indexing terms: Optical fibres, Optical sensors, Nonlinear optics, Microwave circuits and systems*

Experimental data are presented which show for the first time that the back-scattered signals independently generated by stimulated Brillouin scattering in two separate optical fibres may be mixed to produce narrowband radio-frequency signals. This mechanism can be exploited for microwave generation and distributed temperature sensing.

*Introduction:* Stimulated Brillouin scattering (SBS)[1] has recently been proposed as a sensing mechanism for distributed temperature sensors (DTS);[2] in principle the temperature of the remote sensing element can be determined from the frequency shift $\nu_B$ of the back-scattered Brillouin line, where

$$\nu_B = \frac{2n\nu_A \sin\theta/2}{\lambda} \tag{1}$$

where $n$ is the refractive index, $\nu_A$ is the hypersonic velocity, $\lambda$ is the wavelength of the incident beam and $\theta$ is the scattering angle = 180° for full back-scattering.

In a typical monomode optical fibre, $\nu_A \approx 30\,\text{GHz}$ and $d\nu_B/dT \approx 5{\cdot}5\,\text{MHz}/°\text{C}$, hence optical resolutions of 5 MHz are required for a 1°C temperature resolution in a DTS. Although resolutions of this order of magnitude are achievable with high-contrast confocal scanning Fabry–Perot interferometers, absolute optical frequency measurements with this degree of accuracy are difficult to achieve over protracted periods.

An alternative approach for signal recovery commonly used in light scattering experiments, particularly where the linewidth of the scattered light is narrow, is optical heterodyning where the scattered light signal is mixed with the unshifted input laser beam.[3] Light scattered from spontaneous propagating density fluctuations in the medium will be incoherent and the linewidth of the heterodyne signal will be broadened by the dissipative mechanisms in the medium (hypersonic attenuation in the case of the Brillouin scattering). On the other hand, SBS is a coherent process so that the back-scattered light is only subject to random phase fluctuations, thus if this signal is heterodyned with the input laser beam the observed linewidth should be extremely narrow.[4]

In principle this heterodyned signal at $\simeq 30\,\text{GHz}$ could be directly observed using a photodiode with a frequency response in excess of 30 GHz, together with a very high frequency microwave spectrum analyser. Such a solution would be extremely expensive, effectively eliminating this approach for distributed temperature sensing. A more effective solution is to produce a 'reference' SBS signal which can serve as the local oscillator rather than the laser, so that the 'beat' note now occurs at a much lower frequency.

*Experimental:* The experimental arrangement shown in Fig. 1 was used to test the feasibility of generating an optical heterodyne carrier from two SBS signals produced in separate optical fibres.

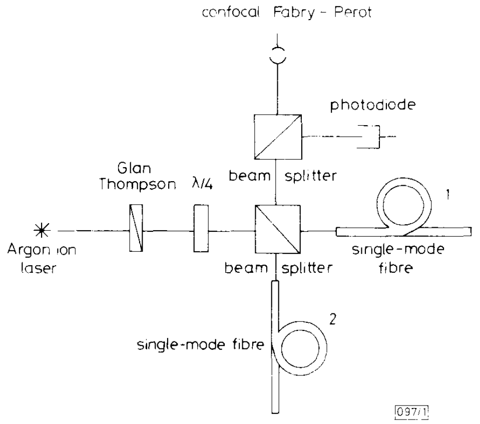

**Fig. 1** *Experimental configuration*

Two back-scattered stimulated Brillouin shifted signals from two 500 m spools of single-mode fibre were analysed with scanning CFP with FSR of 2 GHz. Beat frequency was detected by photodetector and investigated with electronic RF spectrum analyser

Light from a single-frequency argon ion laser operating at 514·5 nm was launched, via a beam splitter, into two 500 m lengths of monomode fibre of slightly different composition. An optical isolator comprising a Glan Thompson prism and a quarter-wave plate was used to prevent any instabilities in the laser output frequency being caused by back-scattered light entering the laser cavity. The back scattered SBS signals from both fibres were combined on the first beam splitter and intensity-divided at the second beam splitter to enable the optical and heterodyne spectra of the light to be simultaneously measured using a high-resolution confocal Fabry–Perot (CFP) and an electronic spectrum analyser.

Fig. 2 shows the optical spectrum of the light analysed with a CFP with 2 GHz free spectral range scanned over 2 orders and both fibres were maintained at room temperature. The frequency shifts of the two stimulated Brillouin lines relative to the input laser pump line are 32·042 GHz and 32·796 GHz. This frequency difference of 754 MHz may be attributed to the different dopant levels in the fibres.

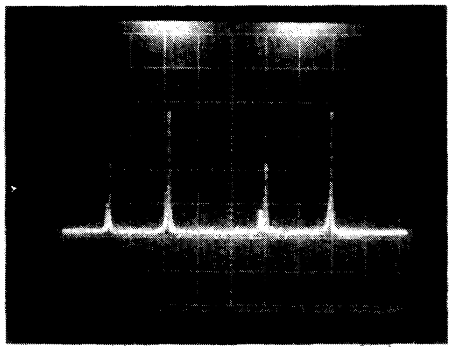

**Fig. 2** *Optical spectrum of light analysed by scanning CFP*

Frequency shift of each stimulated Brillouin line relative to (small) pump line is 32·42 GHz (fibre 1) and 32·796 GHz (fibre 2)

The two back-scattered SBS signals were also detected on a high-speed *pin* photodiode, and the spectrum of its output current was analysed with an HP8590A RF spectrum analyser. Fig. 3 shows the resulting power spectrum (the fibres being maintained under the same conditions as previously), where a very strong < 1 MHz wide peak at 760 MHz is easily identified. The frequency of this peak clearly corresponds to the difference frequency between the two SBS signals, thus one may conclude that optical heterodyning is occurring.

The narrow linewidth of the heterodyne signal also confirms that although the scattering is occurring in different