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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 ν_B of the back-scattered Brillouin line, where

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

where n is the refractive index, v_A is the hypersonic velocity, λ is the wavelength of the incident beam and θ is the scattering angle = 180° for full back-scattering.

In a typical monomode optical fibre, $v_A \approx 30$GHz and $d\nu_B/dT \approx 5{\cdot}5$ MHz/°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 $\simeq 30$GHz could be directly observed using a photodiode with a frequency response in excess of 30GHz, 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.

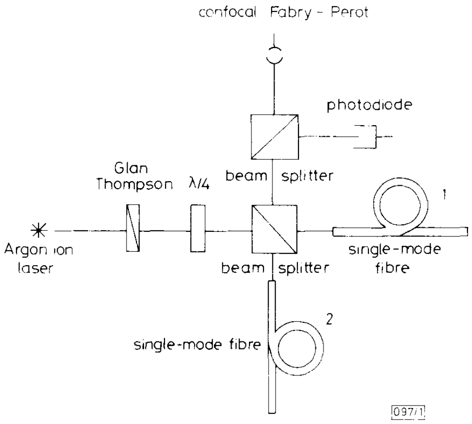

Fig. 1 *Experimental configuration*

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.

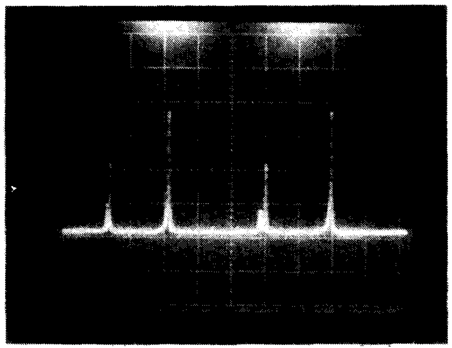

Fig. 2 *Optical spectrum of light analysed by scanning CFP*

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 fibres, a considerable degree of temporal coherence between the stimulated signals must be retained.

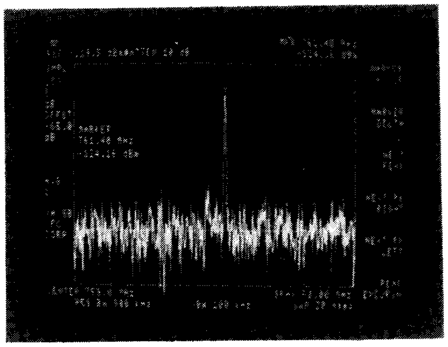

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Fig. 3 *Heterodyne frequency at 761·4 MHz generated at photodiode with both fibres held at room temperature*

Finally, another experiment was performed in which the beat frequency was monitored while the temperature of one of the fibres was lowered, the temperature of the other fibre being held constant. The results of this experiment are shown in Fig. 4 where two traces are superimposed. The low-frequency peak (748 MHz) corresponds to the beat frequency when both fibres were at the same temperature and the high-frequency peak at ≈800 MHz when the differential temperature is 10°C. This corresponds to a frequency shift of $5{\cdot}2\,\mathrm{MHz}\,{}^{\circ}\mathrm{C}^{-1}$ and is in agreement with the temperature sensitivity reported in Reference 2.

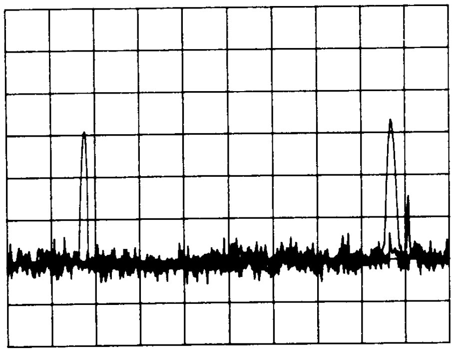

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Fig. 4 *Lower frequency peak (748 MHz) corresponding to beat frequency when both fibres at room temperature*

Higher frequency peak (800 MHz) corresponds to beat note when fibre 1 was heated by 10°C

Conclusions: It has been verified experimentally that a strong heterodyne beat signal with a narrow linewidth can be produced by mixing two SBS signals generated in separate optical fibres. The beat frequency is shown to vary rapidly with temperature; it also depends on the physical properties of the fibre.

It would thus appear that this phenomenon could be exploited to realise: (*a*) a high-resolution distributed temperature sensor; and (*b*) a tunable microwave generator with a large frequency range.

In practice these systems would be based on solid-state laser sources rather than argon ion lasers where, for the DTS application, the solid-state laser would be operated in the pulse mode to determine the spatial distribution of the sensor fibre. Research is currently underway in these laboratories to realise such devices.

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ANALYSIS OF LINEWIDTH OF SEPARATED-ELECTRODE DFB LASER DIODE

Indexing terms: Lasers and laser applications, Optical communications, Semiconductor lasers

We present a new linewidth formula for DFB lasers, which includes the spatial hole burning effect. The linewidth of DFB lasers with three separated electrodes is calculated in various bias conditions. The optimum bias condition is discussed to obtain a narrow linewidth.

Introduction: Separated-electrode DFB lasers are attractive devices for coherent optical communication systems, because the carrier-density distribution along the laser axis is easily controlled by injecting different amounts of current from separated electrodes, and hence mode stability and tunability are improved.[1,2] In this letter we analyse the linewidth of separated-electrode DFB lasers, following an analysis of the mode stability and tunability in a previous letter.[2]

First, we present a new linewidth formula including the effect of the nonuniform distribution of the electric field and the carrier density along the laser axis. The linewidth of DFB lasers with three electrodes is actually calculated in various bias conditions by using this equation. The result shows that the narrow linewidth is obtained when the centre region is pumped more strongly than side regions.

Linewidth formula: The linewidth formula of DFB lasers is given as

$$\delta f = \frac{hfn_{sp}}{4\pi P_{out}}\,\frac{2v_g}{F_c L}\left(\frac{2}{F_c L} + \alpha_l\right)v_g(1 + \alpha^2)F \tag{1}$$

where f is the lasing frequency, n_{sp} is the spontaneous emission factor, P_{out} is the output power from both facets, v_g is the group velocity, L is the cavity length, α_l is the internal loss and α is the linewidth enhancement factor. F_c is the newly introduced electric field confinement factor, which is determined from the electric field distribution and facet reflectivities as

$$F_c = \frac{1}{L}\int_0^L \frac{|E(z)|^2}{\left[\left(\frac{1 - R_1}{1 + R_1}\right)|E(0)|^2 + \left(\frac{1 - R_2}{1 + R_2}\right)|E(L)|^2\right]\Big/2}\,dz \tag{2}$$

where R_1 and R_2 denote power reflectivities at $z = 0$ and L, respectively, and $E(z)$ is the electric field inside the cavity.

On the other hand, F represents the correction factor for the spontaneous emission rate due to the output coupling, which was introduced by Henry,[3] and Kojima and Kyuma[4] as

$$F = \frac{4\beta^2\left(\int_0^L |Z_0|^2\,dz\right)^2}{v_g^2\left|\frac{\partial W}{\partial \tilde{\omega}}\right|^2_{\tilde{\omega} = \tilde{\omega}_0}} \tag{3}$$

$$W = \frac{dZ_+}{dz}Z_- - Z_+\frac{dZ_-}{dz} \tag{4}$$

$Z_-(z)$ and $Z_+(z)$ are virtual electric fields in the cavity which satisfy boundary conditions at $z = 0$ and L, respectively.