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A double-pass configured fibre Mach-Zehnder interferometric optical filter for distributed fibre sensing

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Abstract: A double-pass configured all-fibre Mach-Zehnder interferometric optical filter has been developed and used in a distributed fibre-optic sensor for separation of Rayleigh and Brillouin signals. Its superior performance over a single-pass all-fibre Mach-Zehnder interferometer is highlighted by its 15dB improved rejection of the Rayleigh signal and comparable throughput.

Introduction: The Landau-Placzek ratio, the ratio of the backscattered Rayleigh to the spontaneous Brillouin intensities, has been used for distributed fibre-optic sensing [1, 2]. The Rayleigh signal is insensitive to temperature changes. However, the Brillouin signal has a temperature sensitivity of approximately 0.32% K^{-1}. The achievable temperature resolution of this sensor not only depends on the electrical noise of the detection system, but also on the coherent Rayleigh noise superimposed on the Brillouin signal, due to unsatisfactory rejection of the Rayleigh signal after filtering. This coherent noise is manifested as low frequency perturbations on the Brillouin signal. Hence an optical filter that can provide both high throughput of the Brillouin signal with simultaneous high rejection of the Rayleigh signal would result in an improved temperature resolution.

This paper describes an innovative double-pass all-fibre Mach Zehnder interferometer (DPMZ) used to separate the relatively weak(-15dBr) backscattered spontaneous Brillouin signal from the Rayleigh signal with high throughput of the Brillouin signal and high rejection of the Rayleigh signal. The improvement in signal-to-noise resulting from the enhanced Rayleigh rejection, is approximately 15dB and agrees well with the supporting theoretical comparison between a single-pass all-fibre Mach-Zehnder interferometer (SPMZ) and a DPMZ.

Theory: The anti-Stokes - Stokes separation for Brillouin spectra is approximately 22GHz at 1550nm. A Mach-Zehnder interferometer (MZ) having a free spectral range (FSR) equal to this frequency, requires a fibre path imbalance of ≈ 9.3mm. The differential birefringence of this path imbalance length in the cavity of a MZ is very much less than the beat length of fibre (typically a few cms for single-mode) and can be neglected. For a carefully constructed MZ, the throughput and rejection will be largely determined by the signal bandwidth rather than any imperfections (unbalanced losses, non-ideal coupling coefficients).

Consider a Brillouin signal having a Gaussian spectrum g(ν), of bandwidth Δν, centred at ν_o, filtered by the transfer function of the MZ, and tuned to a maximum at ν_o, so that maximum Brillouin emerges from one output arm. Simultaneously, the Rayleigh signal (also Gaussian) would be tuned to a minimum. The throughput T_n of the Brillouin signal, can be expressed as:

$$T_n = \int_{-\infty}^{+\infty} g(\nu)\,[0.5(1+\cos[2\pi(\nu-\nu_o)/FSR])]^n \, d\nu \tag{1}$$

while the corresponding rejection of the Rayleigh signal, R_n is given by:

$$R_n = \int_{-\infty}^{+\infty} g(\nu)\,[0.5(1 + \cos[2\pi((\nu - \nu_o)/FSR + 1/2)])]^n \, d\nu \qquad (2)$$

where n = 1 and 2 for the SPMZ and the DPMZ respectively. Fig. 1(a) compares the filters' throughput of the Brillouin signal for various bandwidths normalized to the FSR of the MZ. Fig. 1(b) compares the corresponding rejection of the Rayleigh signal. As shown, the DPMZ provides superior rejection of the Rayleigh signal over all bandwidths with a correspondingly slight reduction in the Brillouin throughput.

Experimental demonstration: The experimental schematic is shown in Fig. 2. The pulsed source was a Q-switched erbium-doped fibre laser (QSL) with a centre wavelength of 1557nm, bandwidth ≈ 2GHz, Gaussian spectrum (see Fig. 4 inset), and pulse duration of 100ns. The output from the QSL was monitored at photodetector PD1 via a 94/6 coupler. A 50/50 coupler coupled 300mW into a single mode sensing fibre of length 700m.

A DPMZ with a FSR of 22.3GHz (fibre path imbalance of 9.3mm) was constructed from two continuous lengths of fibre to avoid any splice losses. Fig. 3 shows the configuration of the DPMZ. The backscattered light, comprising Rayleigh and spontaneous Brillouin signals, returning from the sensing fibre, entered at port 1. The DPMZ was tuned such that the Rayleigh signal emerged from port 3 and the Brillouin signal from port 4. A fraction of the Rayleigh signal was extracted at the coupler C1 and used for tuning purposes by maximizing the Rayleigh signal detected on photodetector PD2. Tuning was achieved by controlling the current through a small heating coil adjacent to one of the fibre arms with the other arm insulated to prevent thermal conduction and drift. The isolator blocked the residual Rayleigh after a single pass. The Brillouin signal emerged from port 4 and after passing through the isolator and coupler, re-entered at port 3 to re-emerge from port 2 where it was detected by PD3. The post detection bandwidth was 1 MHZ. The Brillouin signal was averaged 2048 times and stored on a digital oscilloscope.

Fig. 4 shows the resulting Brillouin backscattered plots obtained after filtering by the SPMZ and DPMZ and correcting for a 1.5dB measured differential loss between a single and double pass. Analysis of the two plots indicates that the "Brillouin signal" from the SPMZ is still strongly contaminated by the Rayleigh signal, which is responsible for its apparent higher power and also the perturbations resulting from coherent Rayleigh noise. Such perturbations are negligible on the Brillouin signal obtained using the DPMZ. This signal, together with the actual measured Rayleigh signal, can therefore be used to establish the LPR which was measured to be 29.3.

The improvement in the rejection of the Rayleigh signal using the DPMZ relative to the SPMZ can be determined from Fig. 4. For example, at time 4μs, the DPMZ and SPMZ powers (a.u.) are respectively 2.8 and 1.5 giving a difference of 1.3, the latter representing the residual Rayleigh signal contaminant in the "Brillouin" signal after passing through the SPMZ. For an LPR of 29.3, the improvement in the rejection of the DPMZ is given by $10\log[1.3/(29.3\times1.5)] \approx 15$dB. Such an improvement corresponds to a source normalized bandwidth of 9% (see Fig. 1b). This agrees well with the experimental pulse bandwidth of approximately 2GHz (fig. 4 inset) which is equivalent to a normalized bandwidth of about 9%.

Conclusion: A low cost, double-pass configured all fibre Mach-Zehnder interferometric optical filter has been developed. A theoretical comparison between the SPMZ and DPMZ has shown that whilst there is a reduction in the Brillouin throughput in the DPMZ, as the normalized bandwidth increases, there is a very significant improvement in the rejection of the unwanted Rayleigh signal. The actual throughput of the DPMZ is chiefly determined by small losses through the isolator and 95/5 coupler. The improvement in the Rayleigh rejection is approximately 15dB for a 2GHz bandwidth source. By using a narrower Brillouin pump, together with improvements in the electrical signal-to-noise ratio, the spatial and temperature resolutions can be enhanced and are currently under investigation.

References

[1] WAIT, P.C., NEWSON, T.P.: 'Landau-Placzek ratio applied to distributed fibre sensing', *Optics Comm.*, 1996, **122** (1) pp. 141-146.

[2] DE SOUZA, K., LEES, G.P., WAIT, P.C., NEWSON, T.P.: 'A diode-pumped Landau-Placzek based distributed temperature sensor utilising an all-fibre Mach-Zehnder interferometer', *Electronics letters*, 1996, **32** (23) pp. 2174-2175.

Figure Captions

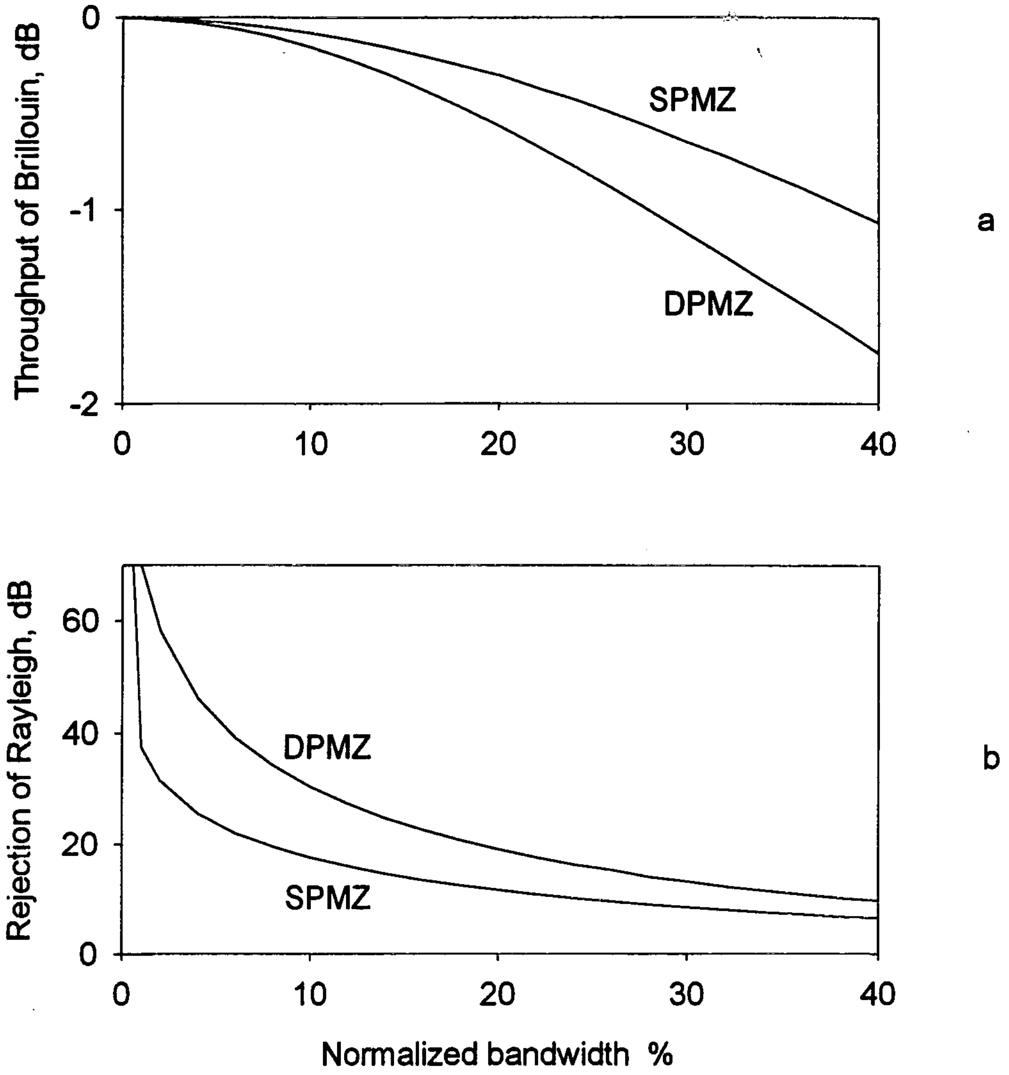
Figure 1 (a) Maximum Brillouin throughput of SPMZ, DPMZ, for a range of normalized bandwidths, modelled for a Gaussian lineshape.

(a) Rejection of Rayleigh in the SPMZ, DPMZ, for a range of normalized bandwidths, modelled for a Gaussian lineshape.

Figure 2 Experimental schematic.

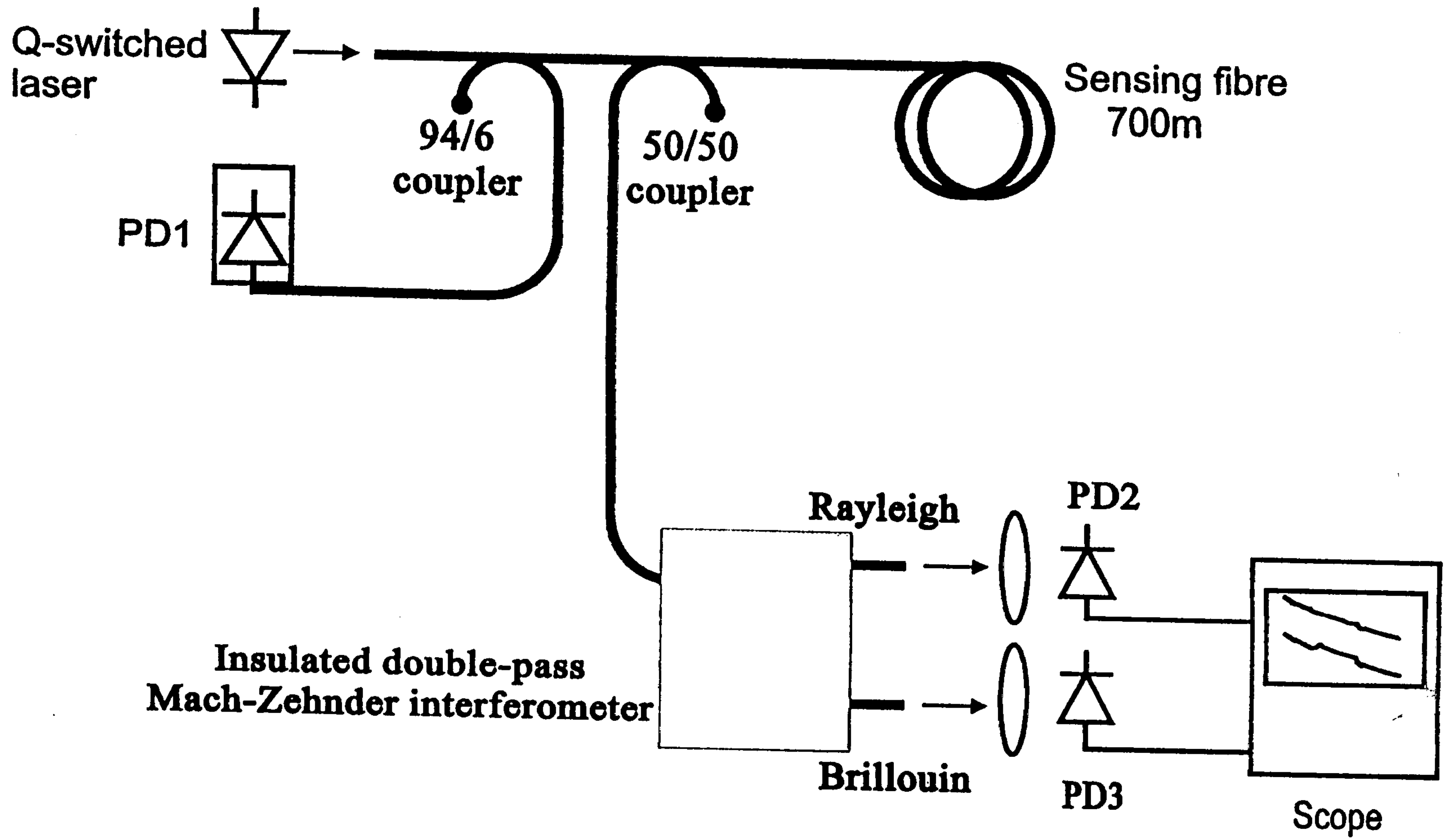
Figure 3 Configuration of DPMZ.

Figure 4 Comparison of Brillouin backscattered plots using the SPMZ and DPMZ. Inset: The pulse spectrum of bandwidth≈2GHz.



0
-1
-2
Throughput of Brillouin, dB
SPMZ
DPMZ
0
10
20
30
40
a
60
40
20
0
Rejection of Rayleigh, dB
DPMZ
SPMZ
0
10
20
30
40
Normalized bandwidth %
b

Fig. 1



Q-switched
laser
PD1
94/6
coupler
50/50
coupler
Sensing fibre
700m
Rayleigh
PD2
Insulated double-pass
Mach-Zehnder interferometer
Brillouin
PD3
Scope

Fig.2

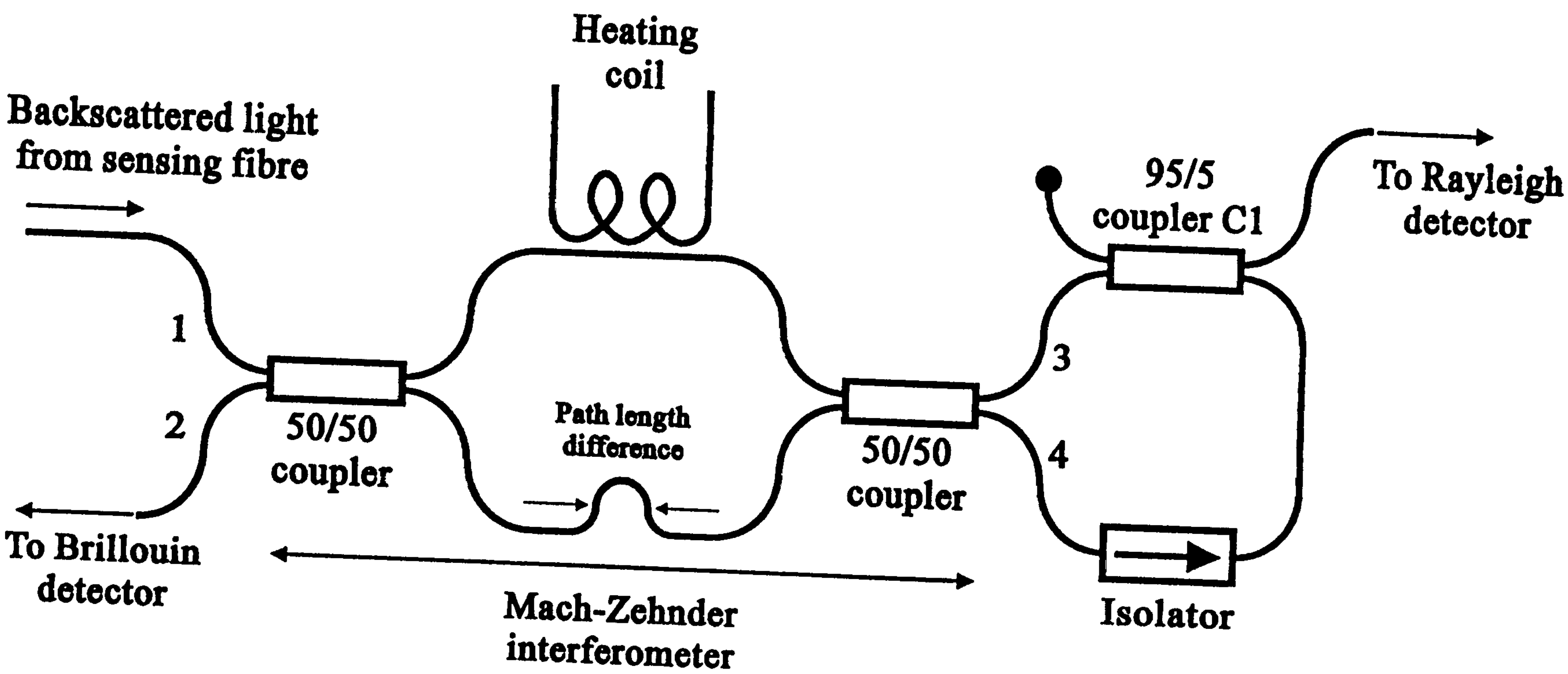

Heating
coil
Backscattered light
from sensing fibre
1
2
50/50
coupler
Path length
difference
50/50
coupler
3
4
95/5
coupler C1
To Rayleigh
detector
To Brillouin
detector
Mach-Zehnder
interferometer
Isolator

Fig. 3

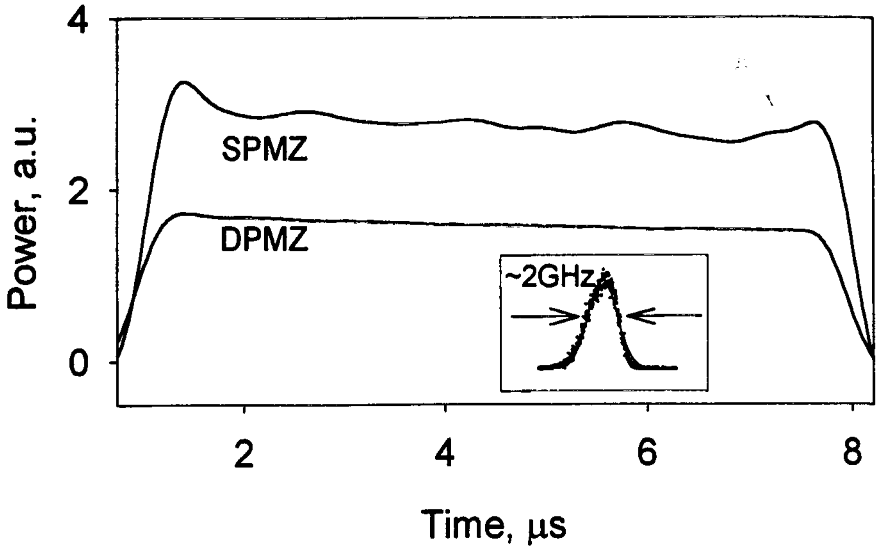


Fig. 4