1731

Location of time-varying strain disturbances over a 40km fibre section, using a dual-Sagnac interferometer with a single source and detector.

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Abstract
This paper reports on results with a novel Sagnac-loop sensor, using spectral slicing of a broadband Er-doped fibre source and has a 40km long sensor loop. Our new WDM arrangement allows use of a single source and optical receiver, yet has low intrinsic losses. The residual optical crosstalk due to non-ideal WDM components is modelled and the initial position dependent results presented.

Introduction

Since the first paper by Dakin et al [1], it has been well known that a Sagnac ring interferometer can be used to locate disturbances occurring at any (non-central) location in the loop. This method is based on the counter-propagating nature of light in the Sagnac interferometer. When a phase perturbation, ϕ, occurs at a distance z from the sensor loop centre, it phase-modulates the light travelling in one direction before light travelling in the other. This results in a net phase modulation, $\Delta\phi$, between the two returning counter-propagating wavetrains which interfere, when combined at the output of the loop. It was shown that $\Delta\phi$ is given by;

$$\Delta\phi(t) \approx \frac{2z}{V_g}\frac{d\phi(t)}{dt} \qquad \text{Eq. 1}$$

where V_g is the group velocity of the guided light.

In the first papers [1,2], the value of $d\phi/dt$ was found by interfering a fraction of the light that had travelled in one direction in the Sagnac loop, with light directly from the source, the latter having been suitably delayed via a fibre loop to form a ***balanced-path*** fibre Mach-Zehnder arrangement.

More recently [3,4,5,6,7], various architectures using twin-Sagnac configurations have been suggested, to avoid the need for accurately balanced paths, and a few have reported to have been experimentally used for (laboratory) location of disturbances over sensor loop lengths of up to 800m. These operated with either twin-source (wavelength multiplexed) [4,8], or intrinsically lossy arrangements with directional 3dB couplers and twin detectors[3,6,7]. (minimum theoretical loss of dual Sagnac system with 3dB couplers = 24dB in each Sagnac).

We now report on a new architecture incorporating the following novel features:-

a) A high-power, short coherence-length, super-luminescent fibre source.
b) A single source, single detector WDM routing system which has only 3dB additional theoretical loss (from spectral slicing of the source), compared to an ideal single Sagnac system, and only 15dB overall minimum theoretical loss. This is 9dB better than the 24dB minimum for the 3dB coupler version [5].

In addition, we report the first disturbance-location results over multi-kilometre (40km!!) sensor loop lengths, although the fibre is still held on fibre spools. A new theory to describe the optical cross-talk effects observed when using non-ideal WDM components is presented.

Principle of operation

Our new configuration is shown in Fig.1. A broadband, low coherence length source is spectrally sliced using WDMs, splitting light into two wavelength bands to form two essentially-independent Sagnac interferometer loops. The first clockwise (CW) direction of Sagnac 1 is formed over a path ABCEFHI, with a fibre delay coil, C, and a piezo electric, (PZT) phase modulator, F. Similarly a second (CW) part of Sagnac 2 interferometer is defined by routing light along the optical path labelled ABDEGHI, again with a PZT stretcher, D, and a delay loop, G. Clearly both Sagnac loops operate bidirectionally. All light is combined onto a common detector, I. In this manner, the effective centre of each of the Sagnac sensor loops is offset in opposite directions, such that each interferometer, despite having a common section, gives a different response to a common perturbation, allowing simultaneous solution of the values of both the disturbance's position and its rate of change.

Each of the Sagnacs were sinusoidally phase biased, at different frequencies, each selected from a set corresponding to the natural Eigenfrequencies of the loops. The bias frequencies were chosen such that even their difference frequency lay above that of the expected disturbance-signals, i.e. the base bandwidth of the sensor output. This bias modulation improves the interferometer sensitivity, by operating at a high slope region of the sinusoidal response, and allows both Sagnacs to share a common detector by providing a different frequency, amplitude-modulated carrier for each. When unperturbed, only even harmonics of the bias modulation can be observed on the detected signal, although, in practice, the detector will normally be band-limited, to respond only up to the 2nd harmonic. However, when a disturbance acts on the loop, odd harmonics appear, which may be demodulated using a lock-in technique. The signals corresponding to the odd and even harmonics for each of the Sagnacs may easily be derived from the detected signals using lock-ins and the outputs may be ratioed in the usual manner [1] to give an amplitude-independent result.

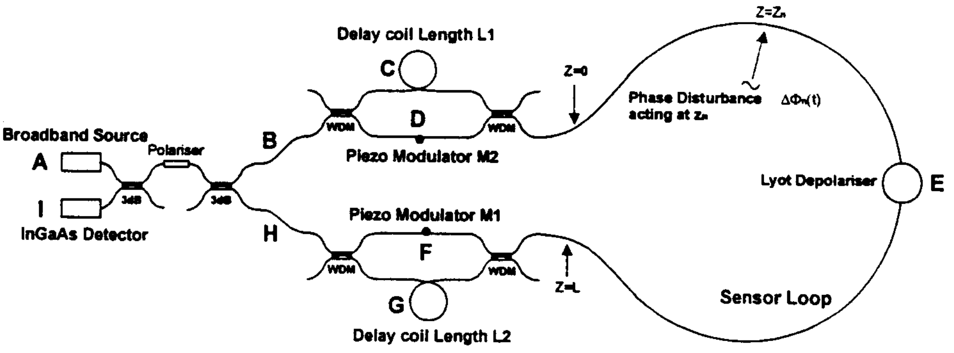

Fig. 1 Experimental configuration of the dual-wavelength . dual-Sagnac sensor

Unfortunately, for a real system, the situation is not quite as simple. Due to non-ideal optical WDM components, there will be a certain amount of residual optical crosstalk, such that a further two paths become weakly allowed. These new paths are labelled 1) ABCEGHI and 2) ABDEFHI. The first allows light to travel without incurring a bias phase modulation, causing a baseband disturbance signal on the detector when the sensor loop is perturbed. Fortunately, the lock-in detection and post-filtering removes this component. The second crosstalk path is potentially more serious, as it allows light to be biased at frequencies corresponding to both Sagnacs. When these signals are demodulated, an error signal results, so a small correction will be needed to remove the effects from this crosstalked path.

Theory

The response expected from each of the Sagnacs is dependent on the rate of change of the disturbance and on its position relative to the sensor-loop centre which, due to the delay coils, will be different for each. This is complicated by the effects of crosstalk and the fact that a single detector is used for both Sagnacs. By considering the amplitude components of the light travelling in both directions around all of the allowed paths and by applying a Jacobian expansion, it was possible to model the expected signals, obtained from lock-in (homodyne) demodulation of the detected signals for each interferometer. These are given by:-

1) 1st Harmonic Sagnac 1,

$$-2\left(\frac{1}{8}+\frac{1-C}{8}\right)\cdot J_1(xa_1)\frac{d\phi_n(t)}{dt}\frac{n}{c}(L+L_1-2z)-2\frac{C}{8}J_0(a_{2c}x)J_1(a_{1c}x)\frac{d\phi_n(t)}{dt}\frac{n}{c}(L-2z) \quad \text{Eq. 2}$$

2) 2nd Harmonic Sagnac 1,

$$2\left(\frac{1}{8}+\frac{1-C}{8}\right)\cdot J_2(xa_1)+2\frac{C}{8}J_0(a_{2c}x)J_2(a_{1c}x) \quad \text{Eq. 3}$$

3) 1st Harmonic Sagnac 2,

$$-2\left(\frac{1}{8}+\frac{1-C}{8}\right)\cdot J_1(xa_2)\frac{d\phi_n(t)}{dt}\frac{n}{c}(L-L_2-2z)-2\frac{C}{8}J_0(a_{1c}x)J_1(a_{2c}x)\frac{d\phi_n(t)}{dt}\frac{n}{c}(L-2z) \quad \text{Eq. 4}$$

4) 2nd Harmonic Sagnac 2,

$$2\left(\frac{1}{8}+\frac{1-C}{8}\right)\cdot J_2(xa_2)+2\frac{C}{8}J_0(a_{1c}x)J_2(a_{2c}x) \qquad \text{Eq. 5}$$

where C is the optical-crosstalk power ratio, x is the bias modulation depth and a_n are constants dependent on the bias frequency and the optical path length. L is the sensor loop length, L_1 and L_2 are the delay coil lengths and J_n is the nth order Bessel function. Also z has been re-defined as the distance at which a phase disturbance, $\phi(t)$, acts, relative to the input end $(z = 0)$ of the sensor loop. The position of the disturbance, $\phi(t)$, can be found by solving the signals simultaneously. I.e., by dividing the resulting signals for each, a ratio will be found which is independent of the rate of change of the disturbance and related only to its position as shown in Fig. 3. In the absence of crosstalk, this position dependent ratio can be shown to be given by;

$$ratio=\frac{J_1(xa_1)J_2(xa_2)(L+L_1-2z)}{J_1(xa_2)J_2(xa_1)(L-L_1-2z)} \qquad \text{Eq. 6}$$

which can be easily solved for the disturbance's position, z.

Experimental and results

The configuration shown in Fig. 1, has been constructed for laboratory trials. A 980nm, 80mW laser diode (Nortel LC91-20) was used to single-end pump, via a fibre WDM, a 30m length of Er/Al-doped fibre having a pump absorption of 4dBm^{-1}. The backward ASE gave a 1mW source (usually, only 200μW was used) with a central wavelength of 1555nm and 40nm FWHM bandwidth. The polariser was a Sifam SP15 device. Biconically fused fibre taper WDMs, with sinusoidal transfer functions, were used to "spectrally slice" light into two output bands with central wavelengths of 1540 and 1570nm respectively. Each output drove a separate Sagnac interferometer loop of 40.1 ± 0.5km length, with delay coil lengths of 4.0 ± 0.2km. Because of the non-ideal nature of these early WDM components (much better ones with "Top-hat" responses are now available) the calculated crosstalk power was relatively high (8.5%). The output from both Sagnacs was detected by a common InGaAs PIN diode (Nortel DPR2SB-43T2), with 0.72 A/W responsivity, and a 150kHz transimpedance amplifier (Theoptics TD40, 100MΩ). Polarisation fading was minimised by including a Lyot-depolariser [9] in the system (3m and 6m lengths of Hi-Bi fibre, of 2.93mm beat length at 1550nm).

Each Sagnac was phase biased using a PZT stretcher, driven sinusoidally at eigenfrequencies of the loop length. Frequencies of 62.497kHz and 48.561kHz were chosen for the two Sagnacs. The even and odd harmonics of these drive frequencies were separated by two separate lock-in amplifiers, with an output filter (base-bandwidth) of 800Hz. (Note: The detector response reduces the amplitude of the third and higher harmonics, before these lock-ins). The bias modulation depth was set to approx 1.55 radians, to maximise the amplitude of the demodulated even harmonics.

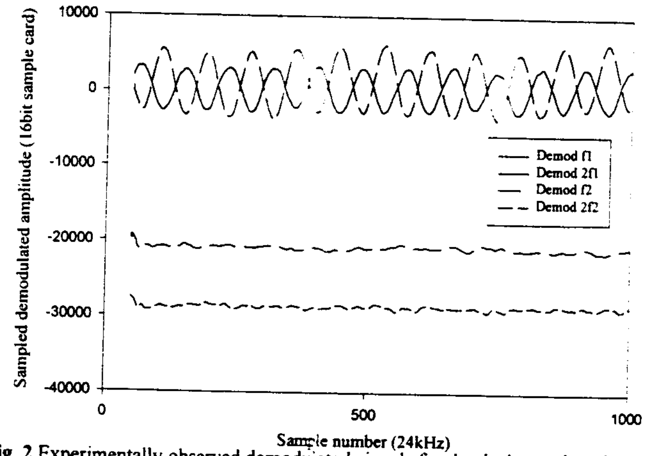

Fig. 2 Experimentally observed demodulated signals for the dual-wavelength Sagnac, (perturbation, 0.1 radians, 283Hz tone).

To reduce the acoustic and seismic background noise present in the laboratory, the interrogation system, with its delay loops, and the sensor loop were housed in acoustically-shielded enclosures, with only a few short fibre test-sections left accessible, allowing an acoustic-tone test disturbance to be applied directly to these known points along the fibre. For this, a simple phase modulator was constructed using a loudspeaker cone, mounted on a thin aluminium sheet, which allowed a length of test fibre to be simply taped onto this sheet, before being set into vibration. Fig. 2 shows the directly-observed fringe pattern, produced when a 0.1 radian amplitude, 283Hz phase disturbance acted on a fibre section at the start of the sensor loop.

The observed fringes were digitally filtered, with a pass-band of approx 20Hz around the disturbance frequency of 283Hz. The resulting waveforms were then divided to yield a position-dependent result, shown in Fig. 3. Shown also is the expected response (dotted lines) for a dual-wavelength Sagnac, assuming ideal WDM components with no optical crosstalk. The same disturbance was applied at various test positions around the sensor loop and the ratio calculated. The positions in the loop, calculated from these results, are shown in Fig. 4.

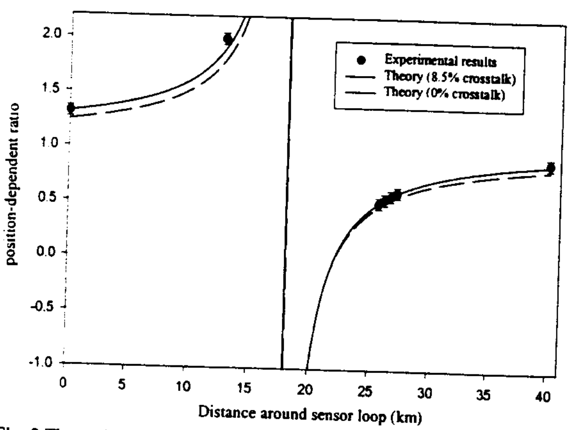

Fig. 3 Theoretical position-dependent ratio for 0% crosstalk. (ideal WDM's) and 8.5% crosstalk. Also shown are the experimentally measured position ratios for a 0.1 radian, 283Hz disturbance.

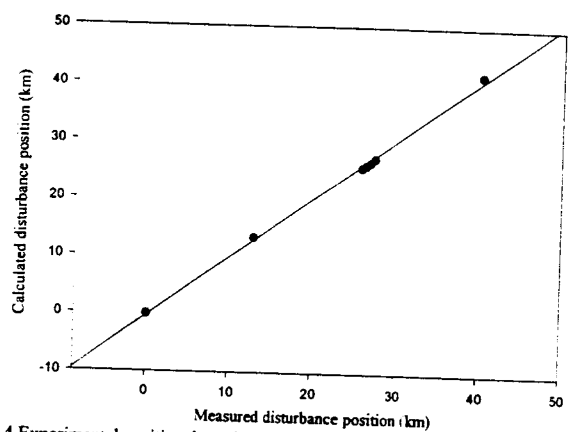

Fig. 4 Experimental positional results, for the dual-wavelength Sagnac interferometer biased at 62.497 & 48.561kHz respectively, perturbed by a 0.1 radian 283Hz disturbance

Conclusion

A novel dual-wavelength Sagnac sensor, using only a single high-powered fibre source and optical detection system, has been presented. This new architecture had a much lower theoretical minimum loss (only 15dB compared to 24dB) when compared to alternative configurations using 3dB couplers. Taking advantage of these low losses, location of a time varying disturbance (283Hz, 0.1 radians) over a 40km length of fibre has been practically demonstrated and the effects of crosstalk between the two Sagnacs discussed and modelled.

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