OFS Monterey, Jan 1992.
573

Sagnac interferometer including a recirculating ring with an erbium-doped fibre amplifier

J. T. Kringlebotn and K. Bløtekjær
University of Trondheim, Norwegian Institute of Technology,
Division of Physical Electronics, Trondheim, Norway

and

C. N. Pannell
University of Southampton, Optical Fibre Group, Southampton, U. K.

Introduction

The use of a Sagnac interferometer as an acoustic sensor has recently been demonstrated [1]. One reason for using a Sagnac interferometer is that the path imbalance is zero, such that no interferometric conversion of the source phase noise to intensity noise occurs. The low frequency response of a Sagnac interferometer increases with increasing loop length, and a very long length of fibre is needed to achieve high responsivity for acoustical frequencies. In this paper we present a scheme where we enhance the low frequency response using a recirculating ring within the Sagnac loop, as shown in fig. 1, thereby increasing the effective length of the Sagnac loop. To increase the number of recirculations an erbium-doped fibre amplifier is incorporated in the ring to compensate for both the coupling and the intrinsic losses of the ring. We also present the results of a noise analysis of a recirculating ring including a fibre amplifier, and show that the dominating noise in our sensor is the beat noise between the signal and the spontanous emission produced by the fibre amplifier.

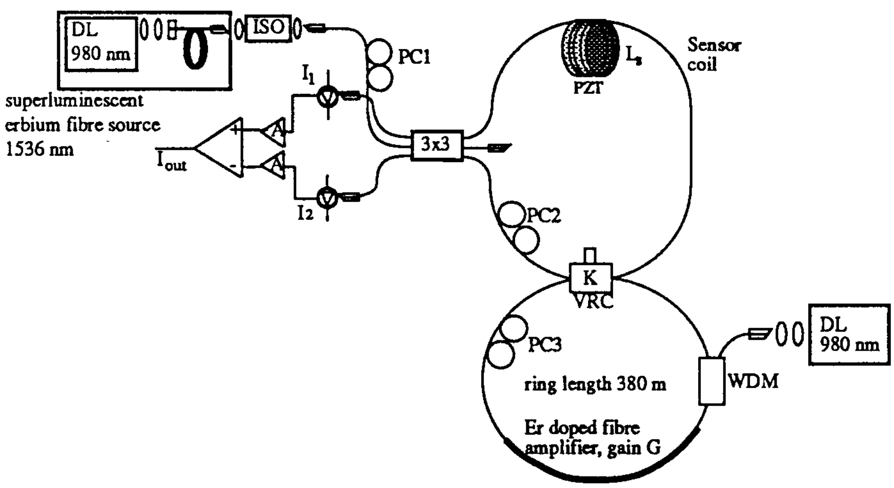

Figure 1. Experimental setup. PZT = piezo-electic transducer, VRC = variable ratio coupler, WDM = wavelength division multiplexer, PC = polarization controller, ISO = optical isolator and DL = diode laser. To prevent oscillation from the fibre end-faces, all ends were angle- polished.

Theory

In the following theoretical analysis the source is assumed to be a single mode laser with a source linewidth much narrower than the linewidth of the erbium amplifier gain spectrum, and a frequency matching exactly the peak frequency ν_0 of this spectrum. We may therefore assume a constant amplifier gain $G = G(\nu_0)$. When the coherence time of the source τ_{coh} is much smaller than the transit time τ of the recirculating ring, the signal output current is a sum of contributions from Sagnac interferometers with increasing loop length:

$$I_s(t) = I_{s0}(t) + \sum_{m=1}^{\infty} I_{sm}(t) \quad (1)$$

where m is the number of circulations in the ring. The individual contributions $I_{sm}(t)$ are given in ref. [1]. For a harmonic signal, the sum can be evaluated, and the total rms signal current as a function of frequency may be written:

$$I_{s,rms}(f) = \frac{\sqrt{6}}{9} A\, R\, P_0\, \Phi \frac{(1-\delta_0)(1-K)^2 U}{K(1-U)} \sqrt{\frac{2(1-\cos[2\pi f\tau])}{1-2U\cos[2\pi f\tau]+U^2}} \quad (2)$$

where $\Phi = \delta\beta\, L_s$ is the amplitude of the acoustically induced phaseshift in the sensor coil. $\delta\beta$ is the amplitude of the acousto-optic modulation of the propagation constant and L_s is the length of the sensor coil. A is the amplification of the two detector currents, R is the responsivity of the detectors, P_0 is the power coupled into the fibre and f is the acoustical frequency . δ_0 is the loss in the variable ratio coupler (VRC), K is the coupling coefficient of that coupler and $U = (1-\delta_0)\, K\, G\, (1-L)$ is the roundtrip transmission which must be less than one, this being the threshold for laser oscillations in the ring. L is the loss in the ring.We have assumed that the sensor coil is short, $L_s << c/f$, and that the signal is weak, $\Phi<<1$. The linear response is a result of using a 3x3 coupler with subtraction of the two outputs, as shown in fig.1.

The output noise current spectrum is obtained as the Fourier transform of the autocovariance function of the output current, as in [2] and [3], but with the fibre amplifier incorporated as an additional noise source. We get three noise terms, the source induced noise as in [2] and [3], the signal-spontaneous beat noise and the spontanteous-spontaneous beat noise. Source induced noise will normally be the dominating noise, but should be cancelled in our differential detection scheme. The dominating noise term is then the signal-spontaneous beat noise. Shot noise is negligible in this setup. With a narrowband laser source there will always be some interferometric conversion of source phase noise due to coherent backscattering. This noise is negligible when using a broadband thermal like source. When $\tau_{coh} << \tau$ we get for the signal-spontaneous beat noise:

$$S_{s,sp}(f) = \frac{2}{9}\, 2\, R^2\, P_0\, \mu\, h\nu_0\, (G-1) \cdot S_{\delta,s\text{-}sp}(f) \quad (3)$$

μ is the amplifier population inversion factor, which is assumed to be one, and $h\nu_0$ is the ASE photon energy. $\mu h\nu_0(G-1)$ is the ASE spectral power in one polarization state [4]. The factor 2/9 is due to the 3x3 coupler. $S_{\delta,s\text{-}sp}(f)$ is a dimensionless transfer function for the recirculating ring, given by

$$S_{\delta,s\text{-}sp}(f) = \frac{(1-\delta_0)^2 K(1-K)}{1-U} \left\{ 1 + \frac{(1-K)U}{K} \left(\frac{\frac{(1-K)(U+1)}{K} + 2(U-\cos[2\pi f\tau])}{1-2U\cos[2\pi f\tau]+U^2} \right) \right\} \quad (4)$$

This function has maxima at frequencies $n\cdot 1/\tau$ were $n = 0,1,2...$
The noise equivalent phaseshift $NE\Phi(f)$ is obtained by setting $I_{s,rms}(f)$ in (2) equal to the rms noise current $I_n(f) = A\sqrt{2S_{s\text{-}sp}(f)B}$, where B is the electrical bandwidth of the detection system. The result is

$$NE\Phi(f) = \frac{K(1-U)}{(1-\delta_0)(1-K)^2 U} \sqrt{\frac{6\mu h\nu_0 (G-1) B\, S_{\delta s\text{-}sp}(f)(1-2U\cos[2\pi\tau f]+U^2)}{P_0(1-\cos[2\pi\tau f])}} \quad (5)$$

Experiment

The experimental setup is shown in fig. 1. Polarization controllers (PC) were used to control both the input polarization state, the reciprocity of the Sagnac interferometer and the birefringence inside the recirculating ring, this being essential to obtain maximum signal-to-noise ratio. Some meters of fibre were wrapped around a pioezo-electric transducer (PZT) which was used to simulate the acoustical signal. As a source we first used a DFB laser with linewidth (FWHM) of 20 MHz designed to operate at 1536 nm. The wavelength of the DFB laser was temperature tuned to match exactly the peak of the erbium amplifier gain spectrum. Secondly, we tried a broadband superluminescent erbium fibre source with 2 nm linewidth (FWHM) (and maximum power 0.45 mW) to reduce the problem with coherent backscattering. The erbium fibre was the same as in the fibre amplifier and no wavelength tuning, and therefore temperature control, was needed to match the fibre source with the amplifier. The erbium amplifier linewidth (FWHM) is 4 nm.

Results and discussion

Fig. 2a shows NEΦ(f) when using the DFB laser. The three solid curves refer to different values of the coupling K, keeping the roundtrip transmission U close to one. Launched source power P_0 = 0.1 mW. Fig. 2a also shows the measured NEΦ(f) for a simple Sagnac interferometer without a recirculating ring, but with the same total length of fibre, which is seen to give the lowest NEΦ! In fig. 2b we plot NEΦ(f) according to eq. (5) for the same source power P_0 and the same values of K, assuming $L = 0.37$, $\delta_0 = 0.04$, $\tau = 1.86\ \mu s$ and $U = 0.99$, this being based on experiments with a pulsed source [4]. NEΦ for the simple Sagnac interferometer is assumed to be shot noise limited [1]. We observe a clear mismatch between the experimental results in fig. 2a and the theoretical curves in fig. 2b, even though the functional forms are similar. This is mainly due to the conversion of source phase-noise because of coherent backscattering associated with the use of the relatively coherent DFB-laser.

This problem should not be present when using the incoherent superluminescent erbium source. The experimental results with this source is shown in fig. 3a, again for different values of K, operating close to threshold. We see a decrease in NEΦ by one order of magnitude which confirms the explanation given above. Fig. 3a also shows that using a Sagnac interferometer including a recirculating ring with a fibre amplifier decreases NEΦ at low frequencies by at least a factor of 2 (at 10 kHz) compared to a simple Sagnac interferometer with the same total length of fibre. The corresponding theoretical curves are shown in fig. 3b, where the same parameters as in fig. 2b are used. However, in this case we can no longer assume a constant gain, and the expressions in (2) - (5) have been modified to include the frequency dependency of the gain. The mismatch is still about one order of magnitude. This is believed to be due mainly to a contribution of source induced noise because of a slight asymmetry in our differential detection scheme. We also see that the experiments exhibit higher noise at frequencies below 5 kHz. This is probably due to 1/f-noise.

The signal frequency response was experimentally found to follow eq.(2), where the low frequency response is enhanced when increasing the roundtrip transission U. The discrepancy between theory and experiment is, therefore, due to the noise.

Conclusion

We have shown that incorporating a recirculating ring with an erbium-doped fibre amplifier in a Sagnac interferometer used as acoustical sensor decreases the noise equivalent phaseshift at low frequencies compared to a simple Sagnac interferometer with the same total length of fibre. The noise penalty using a fibre amplifier in a recirculating ring is, however, quite high. The peak in the noise spectrum centred at $f = 0$ is crucial for low frequency operation such as in our acoustical sensor, and therefore, the advantage of using the recirculating ring with fibre amplifier is limited. However, the active recirculating ring can be very useful in many other applications, for instance as an optical delay line [5]. We have also shown that a superluminescent fibre source is an almost ideal source for sensor applications because of its incoherence and relatively high power. It is also a good source in combination with a fibre amplifier.

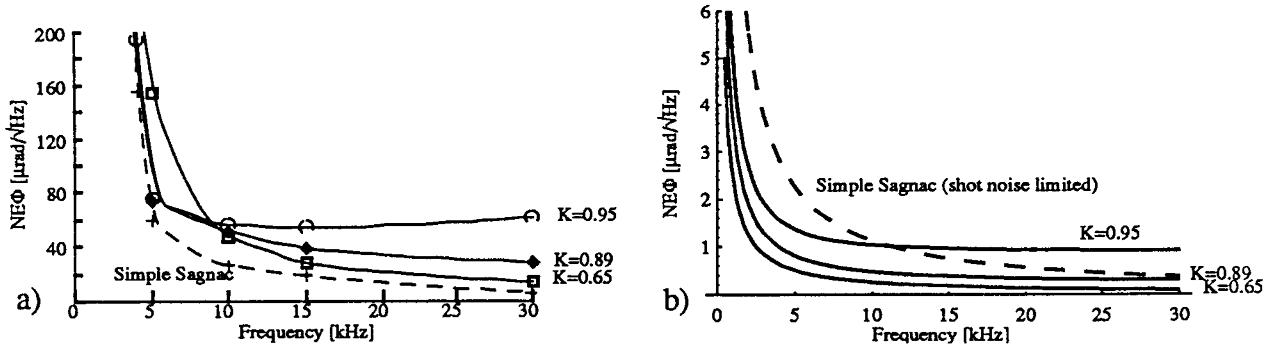

Figure 2. Noise equivalent phaseshift as a function of frequency at different coupling ratios K. The source is a DFB laser. a) experimental results, roundtrip transmission close to threshold. Results with a simple Sagnac loop interferometer without a fibre amplifier is also shown. b) theoretical results, signal-spontaneous beat noise limited. Roundtrip transmission U = 0.99, Shot noise limited noise equivalent phaseshift for a simple Sagnac loop interferometer is also shown.

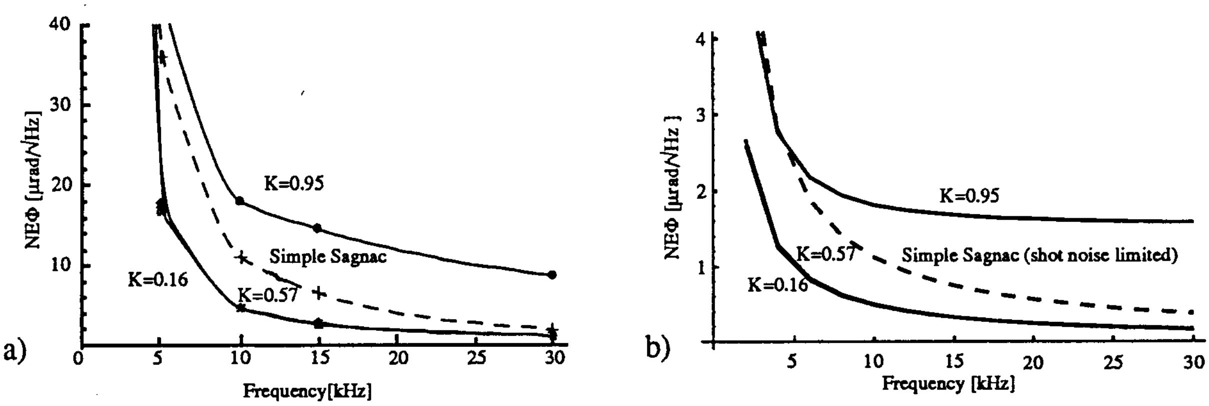

Figure 3. Same as 2, but with a superluminescent erbium source, a) experimental results, b) theoretical results.

Acknowledgements

J. T. K. thanks D. N. Payne for the invitation to work in the ORC, and P. R. Morkel and R. I. Laming for fruitful discussions.

References

1. K. Kråkenes and K. Bløtekjær, "Sagnac interferometer for underwater sound detection: noise properties", Opt. Lett., **14**, 1152 (1989)
2. M. Tur, B. Moslehi and J. W. Goodman, J. Lightwave Technol., "Theory of laser phase noise in recirculating fiber-optic delay lines", **3**, 20 (1985)
3. M. Tur, E. Shafir and K. Bløtekjær, J. Lightwave Technol, Source-induced noise in optical systems driven by low-coherence sources", **8**, 183 (1990)
4. A. Yariv, "Quantum Electronics", 2. ed., Wiley, pp. 293 (1975)
5. J. T. Kringlebotn, P. R. Morkel, C. N. Pannell, R. I. Laming and D. N. Payne, "Amplified fibre delay line with 27000 recirculations", submitted to Electron. Lett.