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Noise in Amplified Fiber Optic Recirculating-Ring Delay Lines

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ABSTRACT

We characterize for the first time the noise in fiber optic recirculating-ring delay lines including doped fiber amplifiers, which are interesting components in many fiber optic sensors because of their enhanced total delay times compared to conventional recirculating-ring delay lines.

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INTRODUCTION

Fiber optic rings are important components in many fiber optic sensors, either as ring resonators, where the source coherence time τ_c is much longer than the ring transit time T, or as recirculating-ring delay lines (RDLs), where $\tau_c << T$. Doped fiber amplifiers have been incorporated in fiber optic rings to compensate for the roundtrip losses, and hence enhance the performance of fiber optic sensors based on such rings [1] – [3].

We here investigate theoretically and experimentally the noise characteristics of amplified fiber optic RDLs (ARDLs), which are essential in all applications of such rings. We concentrate on noise in ARDLs driven by thermal-like sources, but the noise in case of a laser source will also be discussed. The noise characteristics are similar to those of a conventional RDL [4], [5], but they are modified by the introduction of optical gain. The ARDL will also have additional noise terms due to the amplified spontaneous emission (ASE) from the fiber amplifier. The presented theoretical model of noise in ARDLs is based on the statistics of the optical signal and ASE fields involved, and follows the lines of [4] and [5] for conventional RDLs. Our model provides a useful tool for analyzing future fiber optic systems including fiber amplifiers.

THEORY

An optical signal field $\mathbf{E}_0(t)$ is launched into an ARDL with a transit time T through a 2x2 coupler with power coupling coefficient K and power excess loss δ_0, as shown in Fig. 1. $\mathbf{E}_{ase}^{\pm}(t)$ is the clockwise (+) and counterclockwise (-) unpolarized ASE fields emitted from the amplifier, and $G(\nu)$ is the amplifier gain spectrum. η_T is the power loss in the fiber ring.

The electrical noise power spectrum, S(f), of the output detector current i(t) is obtained as the Fourier-transform of the autocovariance function $C_i(t)$ of i(t). $C_i(t) = \langle i(t)i(t+t)\rangle - \langle i(t)^2\rangle$, where $i(t) = \mathbf{E}_{out}(t)\mathbf{E}_{out}^*(t)$, where $\mathbf{E}_{out}(t)$ is the (normalized) total output optical field. If we assume a constant T and ignore the dispersion in the fiber, this field can be written as

$$\mathbf{E}_{out}(t) = \sum_{m=0}^{\infty} A_m \mathbf{E}_0(t') \otimes h_m(t') + \sum_{m=0}^{\infty} B_m \mathbf{E}_{ase}^{+}(t')^{i} \otimes h_m(t') \qquad (1)$$

where the first term is the output amplified optical signal field, and the second term is the output ASE field. A_m and B_m are complex weighting factors depending on δ_0, K and η_T. A_m is equal to F_m in [4], and $B_m = [(1-\delta_0)(1-K)]^{1/2} [jU_{pass}^{1/2}]^m$, where $U_{pass} = (1-\delta_0)(1-\eta_T)K$ is the power roundtrip transmission in a ring with no gain. $h_m(t)$ is a transfer function representing m recirculations in the fiber ring. This transfer function, which is assumed to be polarization independent, is the inverse Fourier transform of an optical frequency response function $H_m(\nu)$, where $|H_m(\nu)| = G(\nu)^{m/2}$.

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In the following we assume a polarized thermal–like source, with a polarization state matching one of the eigenstates of the ring. The calculated output electrical noise power spectrum can then be expressed as a sum of three terms:

$$S(f) = \rho^2 \int_{-\infty}^{\infty} S_S(\nu)S_S(\nu+f)d\nu + 2\rho^2 \int_{-\infty}^{\infty} S_N(\nu)S_N(\nu+f)d\nu$$

$$+ \rho^2 \int_{-\infty}^{\infty} \left[S_S(\nu)S_N(\nu+f) + S_N(\nu)S_S(\nu+f)\right]d\nu \quad (2)$$

where the first term is the source induced noise (signal–signal beat noise), which can be expressed as a self correlation of the output optical signal spectrum $S_S(\nu)$, the second term is the spontaneous–spontaneous (sp–sp) beat noise, which can be expressed as a self correlation of the output optical ASE spectrum $S_N(\nu)$, where the factor of 2 is due to the two polarization eigenstates of the ring, and the third term is the signal–spontaneous (s–sp) beat noise, which is given by a correlation between the output optical signal and ASE spectra. ρ is the detector responsivity.

The output optical signal spectrum can be written as

$$S_S(\nu) = S_0(\nu) \left| \sum_{m=0}^{\infty} A_m \exp[-j2\pi\nu Tm] G(\nu)^{\frac{m}{2}} \right|^2 \quad (3)$$

where $S_0(\nu)$ is the input signal spectrum. Depending on the magnitude of the gain, $S_S(\nu)$ will have dips or peaks at integer multiples of 1/T where the optical frequency component of the input signal spectrum satisfies the resonance condition of the ring. When the gain equals the losses, the output signal spectrum is smooth.

The output ASE spectrum in each of the two polarization eigenstates is

$$S_N(\nu) = S_{ase}(\nu) \left| \sum_{m=0}^{\infty} B_m \exp[-j2\pi\nu Tm] G(\nu)^{\frac{m}{2}} \right|^2 \quad (4)$$

where $S_{ase}(\nu) = n_{sp}h\nu[G(\nu)-1]$ is the ASE spectrum in each of the two eigenstates at the end of the fiber amplifier, where n_{sp} is the spontaneous emission factor, which for complete population inversion along the fiber amplifier is equal to one. The output ASE spectrum will always have peaks at integer multiples of 1/T because all recirculating ASE fields see the same phaseshift in the coupler.

As a result of the correlations in (2), we expect that the output electrical beat noise spectra will have peaks or dips at integer multiples of 1/T, with widths equal to twice the optical resonator linewidth.

RESULTS

The electrical source induced noise spectrum and the sp–sp beat noise spectrum were measured with an RF spectrum analyzer, using a fiber optic ring consisting of a 4.5 m long erbium doped fiber, pumped through a wavelength division multiplexer by a 980 nm diode laser, and a 380 m long single mode fiber. The center wavelength of the source matched the 1535 nm peak in the gain spectrum. Two polarization controllers were used to ensure that the signal polarization state was equal to one of the eigenstates of the ring.

Fig. 2a) shows the source induced noise power spectrum with a thermal-like SLD source, for various values of the laser diode pump current I_p, and thereby the gain. W is the spectrum analyzer bandwidth and P_0 is the input signal power. Fig. 2b) shows the corresponding theoretical spectrum for various values of the peak power roundtrip transmission, $U = U_{pass}G$, below threshold ($U = 1$) for laser oscillations in the ring. G is the peak gain. The width of the peaks is twice the resonator linewidth as expected.

Fig. 3a) shows the source induced noise power spectrum with a DFB laser source. While the source induced noise with a thermal-like source consists of both interferometrically converted phase to intensity noise and filtered intensity noise [5], the source induced noise with a laser source only consists of phase induced intensity noise [4], and the noise characteristics are different from the case of a thermal-like source. The noise power spectrum is equal to that of a conventional RDL [4], but with U_{pass} replaced by $U = U_{pass}G$. We see from Fig. 3a) that the source induced noise spectrum can have either maxima or minima at integer multiples of 1/T, depending on the laser diode pump current and hence the gain. This is in agreement with theoretical spectrum shown in Fig. 3b) for various values of the power roundtrip transmission. Note that the pump current for the upper experimental spectrum is above threshold for ring laser oscillations, and hence the spectrum includes beating between the ring laser modes.

For output signal powers higher than output ASE powers the s–sp beat noise will dominate over the sp-sp beat noise, but it is usually much smaller than the source induced noise, and can therefore not easily be observed experimentally.

Fig. 4 shows the theoretical s–sp beat noise spectrum, again for various values of the roundtrip transmission U. A single mode laser source is assumed, but the s–sp beat noise spectrum is essentially the same with a thermal–like source. Depending on the magnitude of the gain, the s–sp beat noise spectrum can have either peaks or dips at integer multiples of 1/T. When $U = K$, the gain equals the losses, and the s–sp beat noise spectrum is smooth because the optical signal spectrum is smooth.

Fig. 5a) shows the measured sp–sp beat noise spectrum with the source turned off, for a pump current just below threshold, and for a pump current above threshold, in which the spectrum is a ring laser beat spectrum. The corresponding theoretical spectrum is shown in Fig. 5b) for two values of the roundtrip transmission U. Like the source induced noise spectrum with a thermal–like source, the sp–sp beat noise spectrum will always have maxima at integer multiples of 1/T, as expected from the correlation process.
Note that the width of the resonances in all experimental plots is limited by the spectrum analyzer bandwidth.

REFERENCES

[1] J. T. Kringlebotn, K. Bløtekjær, and C. N. Pannell, "Sagnac interferometer including a recirculating ring with an erbium-doped fiber amplifier" Proc. 8th Optical fiber sensors conference, pp. 6–9, 1992.

[2] D. N. Chen, K. Motoshima, M. M. Downs, and E. Desurvire, "Reentrant Sagnac fiber gyroscope with a recirculating delay line using an erbium-doped fiber amplifier," IEEE Photon. Technol. Lett., vol. 4, pp. 813–815, 1992.

[3] J. T. Kringlebotn, "Amplified fiber ring resonator gyro," IEEE Photon. Technol. Lett., vol. 4, pp. 1180–1183, 1992.

[4] M. Tur, B. Moshehi, and J. W. Goodman, "Theory of laser phase noise in recircu–lating fiber-optic delay lines," J. Lightwave Technol., vol. 3, pp. 20–30, 1985.

[5] M. Tur, E. Shafir, and K. Bløtekjær, "Source-induced noise in optical systems driven by low-coherence sources, "J. Lightwave Technol., vol. 8, pp. 183–189, 1990.

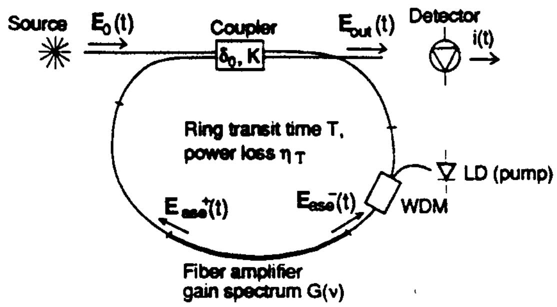
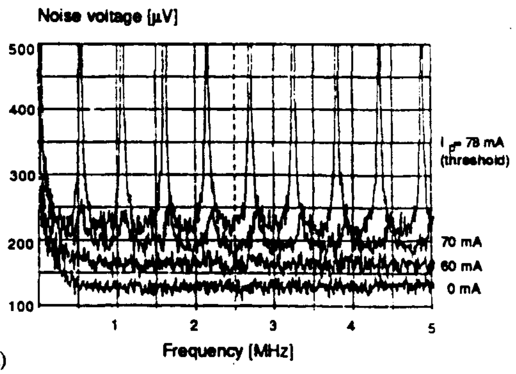
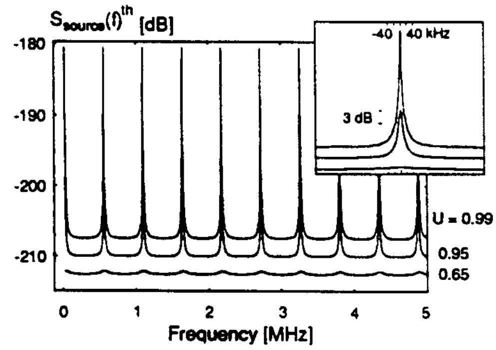


Fig. 1 Amplified fiber optic recirculating-ring delay line



2a)



2b)

Fig. 2. a) Source induced noise power spectrum with SLD for various pump currents I_p. $P_0 = 100\ \mu W$, $K = 0.65$, $W = 10$ kHz. b) Corresponding theoretical spectrum, $S_{source}(f)^{th}$, for various values of U. The inset shows one of the maxima.

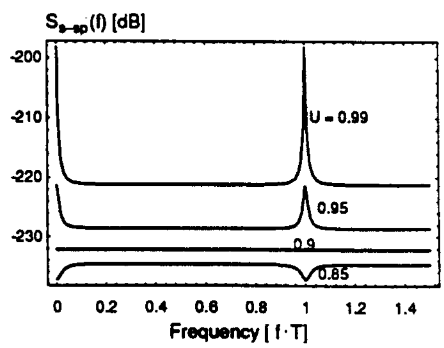
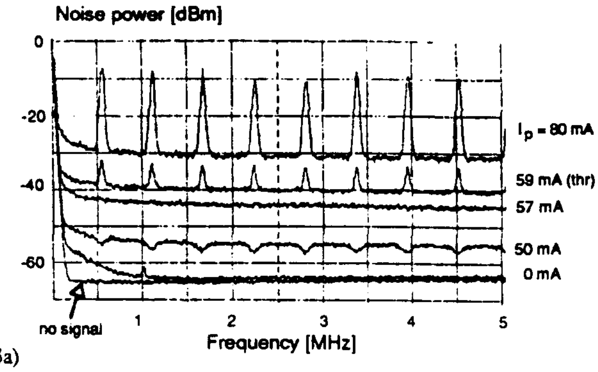
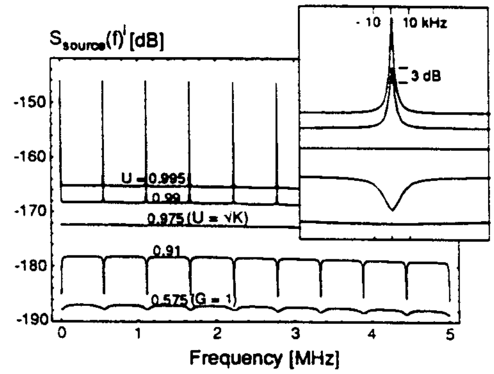


Fig. 4 $S_{s-sp}(f)$ with a laser source as a function of the frequency in units of 1/T for various values of U. $P_0 \approx 50\ \mu W$ and $K = 0.9$.

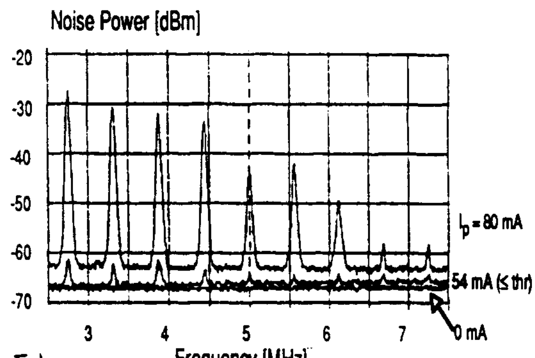


3a)

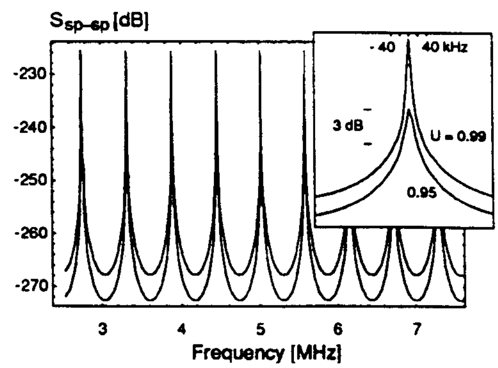


3b)

Fig. 3. a) Source induced noise power spectrum with DFB laser source for various values of I_p. $P_0 \approx 50\ \mu W$, $K = 0.95$, $W = 30$ kHz. b) Corresponding theoretical spectrum for various values of U.



5a)



5b)

Fig. 5. a) Experimental sp–sp beat noise spectrum. $K = 0.9$ and $W = 30$ kHz.b) Corresponding theoretical spectrum, $S_{sp-sp}(f)$, for two values of U.