Radio-frequency ring resonators for self-referencing fiber-optic intensity sensors

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Abstract. A theoretical and experimental study of radio-frequency ring resonators (RR) for referencing and improving the sensitivity of fiber-optic intensity sensors (FOS) is reported. The separation between lead and transducer losses in the FOS is solved by converting the light intensity fluctuations to be measured into RR losses that produce high amplitude variations in the proximity of the RR resonance frequencies. Two different self-referencing techniques are developed. Via the definition of the measurement parameter R_M, sensor linearity and sensitivity are analyzed. A calibration using an optical attenuator is reported to validate the model. [DOI: 10.1117/1.1883566]

Subject terms: fiber-optic sensors; self-referencing; intensity-based sensors; ring resonators.

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1 Introduction

Fiber-optic intensity sensors (FOS) based on multimode[1] (MM) and single mode[2] (SM) fibers need a self-referencing method to minimize the influences of long-term aging of source characteristics, as well as short-term fluctuations in optical power loss in the leads to and from the transducer. Time division, wavelength normalization,[1,3] and frequency-based self-referencing methods[4,5] based on MM fibers, and a Michelson topology with SM fibers[6] have been reported.

In this letter, we propose a novel frequency-based approach using a ring resonator (RR), with an improved sensitivity. Its principle and properties are discussed and tested.

2 Theoretical Analysis

The new sensing scheme is a RR and a FOS (see Fig. 1). The RR operates under an incoherent regime, so $\tau \gg Tc$, where Tc is the source coherence time and τ is the loop transit time. The RR relative output power, P_3/P_1, is given by:

$$g\sqrt{\frac{K^2+[(1-2\cdot K)\cdot H]^2+2\cdot K\cdot(1-2\cdot K)\cdot H\cdot\cos(\omega\cdot\tau)}{1+(K\cdot H)^2-2\cdot K\cdot H\cdot\cos(\omega\cdot\tau)}}, \quad (1)$$

$$H=10^{-\alpha L/10}\cdot A\cdot g\cdot F(m), \quad (2)$$

where $g=(1-\gamma)$, m is the measurand, $F(m)$ is the FOS calibration curve, γ and K are the coupler excess loss and coupling coefficient ω is the modulating signal, pulsation α is the fiber attenuation coefficient in dB/km, A is an attenuation, and L is the loop length. The FOS modulates the RR loss, H, and the output power frequency P_3/P_1, see inset of Fig. 1 for $K\in(0-0.5)$; there is a constant maximum if $\cos(\omega\tau)=+1$, and a dependent on H minimum if $\cos(\omega\tau)=-1$. The *frequency normalization method* is based on the sinusoidal modulation of the optical power source at two frequencies f_1 and f_2, as seen in Figs. 1 and 2. In this method, the measurement parameter is R_{M1}:

$$R_{M1}=\frac{\left|\frac{P_3}{P_1}\right|(\omega,\tau)}{\left|\frac{P_3}{P_1}\right|_{|\cos(\omega\tau)=1}}=\frac{|P_3|(\omega,\tau)}{|P_3|_{|\cos(\omega\tau)=1}}. \quad (3)$$

The *two ports normalization method* uses a single frequency (f_1), a coupler inside the RR for measuring P_4, and two down leads under identical external conditions; and the measurement parameter is R_{M2}:

$$R_{M2}=\frac{|P_3|(\omega,\tau)}{|P_4|_{|\cos(\omega\tau)=-1}}. \quad (4)$$

The normalized sensitivity of the whole system is:

$$\frac{1}{R_{Mi}}\left(\frac{\partial R_{Mi}}{\partial m}\right)=\frac{\partial R_{Mi}}{R_{Mi}\partial H}\left(\frac{\partial H}{\partial m}\right)=S_{Mi}k_1S_F \quad (5)$$

being $S_F=\delta F/\delta m$ the FOS sensitivity, k_1 is a constant and $i=1,\ 2$ for the frequency and two ports normalization method, respectively. This system sensibility is enhanced by S_{Mi}. If f_1 is the resonance frequency, S_{M1} is given by:

$$\frac{-(1-K)^2}{(1+K\cdot H)\cdot[K-(1-2\cdot K)\cdot H]} \quad (6)$$

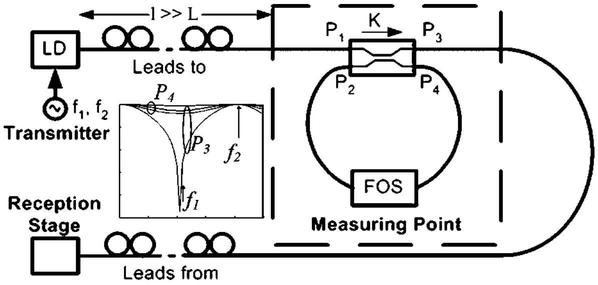

Fig. 1 General scheme of a RR for self-referencing FOS. Inset shows RR relative output powers versus frequency for different *H* values to illustrate operation.

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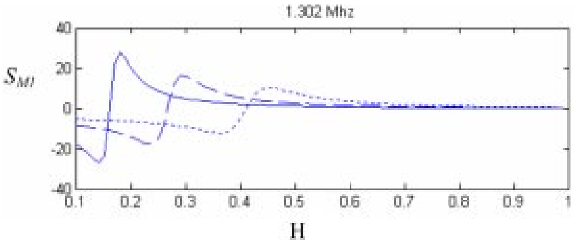

Fig. 2 Normalized sensitivity, S_{M1}, versus H, in the *frequency normalization* method. $f_1 = 1{,}302$ MHz, $L = 1067$ m, $\gamma = 0.05$, and (_): $K = 0.11$, (– –): K=0.17, (...): $K = 0.22$.

So S_{M1} tends to ∞ if $H \rightarrow H_0 = K/(1-2K)$,

The presence of noise limits the real value of the sensitivity. S_{M1} is plotted at Fig. 2, for a f_1 frequency of 1,302 MHz, in a RR with a loop length of 1067 m. There is an inflection point for every K at the H_0 value. For every quiescent point, a certain K can be selected for achieving high sensitivities. S_{M2} behaves quite similar to S_{M1}.

3 Measurements

The experimental setup is made of a LD of 1.5 μm, with 5 MHz linewidth, internally modulated with a signal coming from the tracking generator of a RF spectrum analyzer. The sensing scheme (see Fig. 1) is made of a polarization maintaining 2×2 variable ratio fiber coupler with pigtails of 1 m, 1067 m of standard SM fiber, and an attenuator simulating the FOS. f_1 is 1.302 MHz, f_2 is 1.207 MHz, and $K = 0.22$. The calibration curves, for both self-referencing methods, are reported in Fig. 3. There is a great agreement between theory and measurements, and the system reveals good sensitivity compared to other topologies;[5] even though f_1 is not in the resonance frequency. Measurements variations, around 4%, could be improved using a low coherence source in order to decrease the source induced noise.

4 Conclusions

Two different self-referencing methods for intensity fiber-optic sensors are described and their sensitivities are theoretically analyzed. The proposed scheme, using RR operating under incoherent regime, is flexible because the operation point and sensitivity is controlled by a coupling coefficient. Experimental calibration curves are reported validating the utility of the model developed. This configuration has a better sensitivity to other topologies.

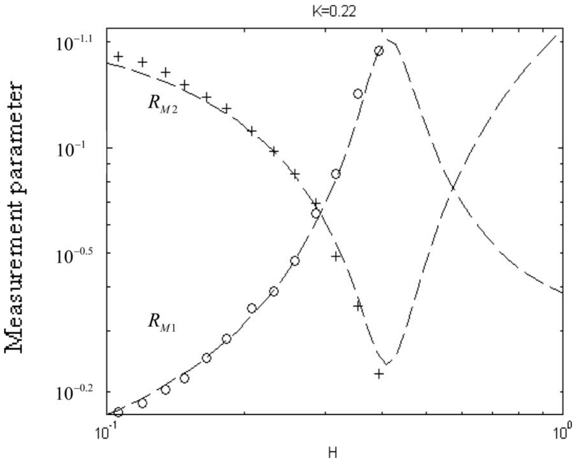

Fig. 3 Calibration curves for $K = 0.22$: measurements R_{M1} (○) and R_{M2} (+) and simulations (dashed line).

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