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Versatile all-fiber slow-light assisted sensor

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ABSTRACT

We present theoretical and experimental results on a slow-light assisted all-fiber configuration that can be used for efficient sensing of a variety of parameters (pressure, displacement...). In particular, we report here a structure that can be transformed into a slow-light assisted displacement sensor capable of sub-micrometric resolution values with a potentially simple intensiometric measurement scheme. The basic element in the structure is a lossy ring resonator tuned close to the critical coupling regime. In this working regime, the resonator transfer function displays extremely high group delay values close to the resonances, and, accordingly, a large sensitivity to additional losses. A mechanic transducer transforms displacement into small additional losses in the ring. This leads to strong variations in the log transmission of the resonances, which are shown to scale with the group index. This scheme shows orders of magnitude sensitivity enhancements over a conventional bending-loss configuration. We believe that this structure can be further developed to provide large sensitivity enhancements to conventional intensiometric fiber sensors.

Keywords: slow light, ring resonators, group delay, group index, Kerr effect.

1. INTRODUCTION

Light-matter interactions are weak in most optical media in conventional conditions. Slow light structures allow a large reduction of the group velocity of the light signals travelling through them, and, as a consequence, a strong confinement of the electromagnetic field and a great enhancement of light-matter interactions [1]. These interactions include various linear and nonlinear effects as well as spontaneous emission.

From the point of view of fiber sensors, the possibility of enhancing light-matter interactions may favor the development of more compact and sensitive devices. Some research effort has been devoted to understanding the exact enhancement values given by slow light in different light-matter interactions. For instance, the role of slow light in enhancing nonlinear effects has been theoretically investigated [2, 3]. The enhancement factor in Kerr effect scales as n_g^2 (n_g being the group index of the structure) due to the combined effect of two contributions: the longer transient time of light pulses in the medium and the higher energy density due to spatial pulse compression. It has also been theoretically and experimentally proved that the extreme dispersion of slow light can lead to an enhancement in the spectral sensitivity of interferometers given by n_g [4]. The role of slow light in enhancing gyroscope performance [5] and Beer-Lambert-Bouguer (BLB) absorption [6, 7] has also been theoretically and/or experimentally investigated. Generally speaking, light-matter interactions have been found to be only enhanced in *structural* slow light systems (e.g. coupled resonators, Bragg gratings, etc.). *Material* slow light systems (e.g. stimulated Brillouin/Raman scattering, parametric amplification, etc.) do not follow the same rules, the origin of this difference being that the electromagnetic energy velocity in material slow light does not depend on the group index [8]. From the fiber sensing point of view, it is therefore interesting to find structural slow light media, i.e. passive structures in which the group index could be tuned widely. Such a system could be considered as a platform for the development of slow-light assisted sensors.

In this paper we demonstrate theoretically and experimentally a wide range tuning of the group delay in a lossy fiber-based ring resonator. This structure is shown to exhibit strong sensitivity enhancements when the resonator is tuned to the critical coupling regime. For demonstrative purposes, we develop a simple displacement sensor with sub-micrometric resolution. We believe that this structure could become a basic building block in future slow-light-assisted fiber sensors.

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2. THEORETICAL ANALYSIS

In this section we perform a theoretical study of slow and fast light in lossy fiber ring resonators. We show that, depending on the coupling ratio and the loss in the resonator, the group delay of the ring resonator can be tuned from strong delay to strong advancement, including situations of negative group delay.

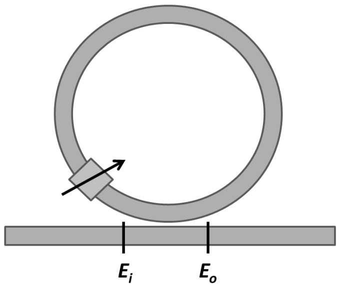


Fig.1: Fiber-based ring resonator considered. Light travels from left to right.

We consider the structure depicted in Figure 1, i.e. the typical fiber ring resonator with a variable loss element inside. Our analysis of this structure is similar to the analysis done by Heebner et al. [9] for resonator-coupled waveguides. A transfer function can be found for the case of the lossy resonator:

$$\frac{E_o}{E_i} = \frac{\kappa \exp\left(\frac{i\omega nL}{c}\right) - a}{\exp\left(\frac{i\omega nL}{c}\right) - \kappa a} \tag{1}$$

Where κ and a are, respectively, the coupling ratio and the attenuation in the resonator (in unitless form). As expected, this transfer function leads to resonances in the spectrum with a periodicity given by c/nL. These resonances exhibit steep dispersion slopes close to the center, leading to large group delays. We can theoretically evaluate the group delay in the resonances by finding the phase of expression (1), obtaining the derivative with respect to ω, and evaluating the obtained expression at the resonant frequencies. The resulting expression is:

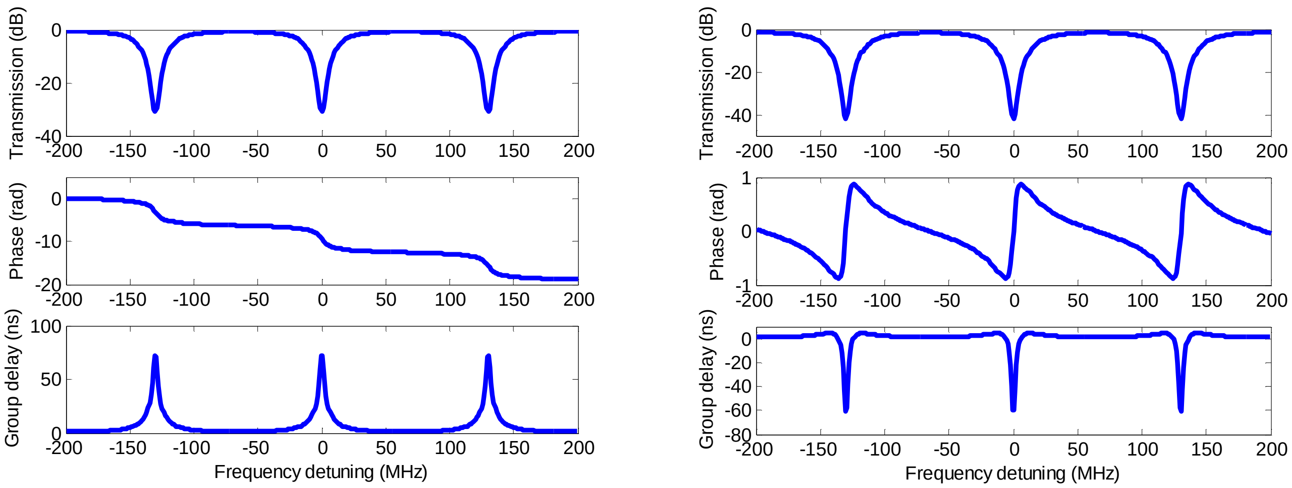
$$\tau_g = \frac{nL}{c} \cdot \frac{a\left(1-\kappa^2\right)}{\kappa\left(a^2+1\right) - a\left(\kappa^2+1\right)} \tag{2}$$

We can therefore see that the delay in the resonator can be expressed as the regular single-pass delay of the resonator (nL/c) multiplied by a factor that may be varied continuously by changing only the attenuation and/or coupling ratio in the resonator. It can be easily shown that, when the losses exceed the coupling (undercoupling), negative group delays can be found at the resonances, while they remain positive in the opposite case (overcoupling). A discontinuity in function (2) is found for the critical coupling case ($a=\kappa$), where the group delay function displays a vertical asymptote, taking values of $-\infty$ when $a \rightarrow \kappa^-$ and $+\infty$ when $a \rightarrow \kappa^+$. The evolution of the group delay close to the critical coupling can be described by $\tau_g \propto (\kappa-a)^{-1}$. The qualitatively different behavior of both regimes is depicted in Fig. 2.

We can now also evaluate the transmission coefficient of the resonator in the center of the resonance as a function of the attenuation and coupling coefficients. The power transmission coefficient can be written as:

$$T = \left|\frac{a-\kappa}{\kappa a - 1}\right|^2 \tag{3}$$

As it can be seen, in the transmission coefficient, the case $a=\kappa$ (critical coupling) corresponds to the case in which the transmission at the resonance center goes to zero. It is interesting now to evaluate the sensitivity of the log transmission to small attenuation/absorption changes in the ring ($S=d[\log(T)]/da$). Close to the critical coupling, the sensitivity can be seen to follow a similar dependence as the group delay $S \propto (\kappa-a)^{-1}$. Hence the sensitivity can also be strongly enhanced by simply working closer to the critical coupling regime. It is interesting to stress that this enhancement is not related to the Q factor of the resonator. In fact the energy circulating in the loop in critical coupling conditions remains comparable to the energy fed directly through the coupler to the output.

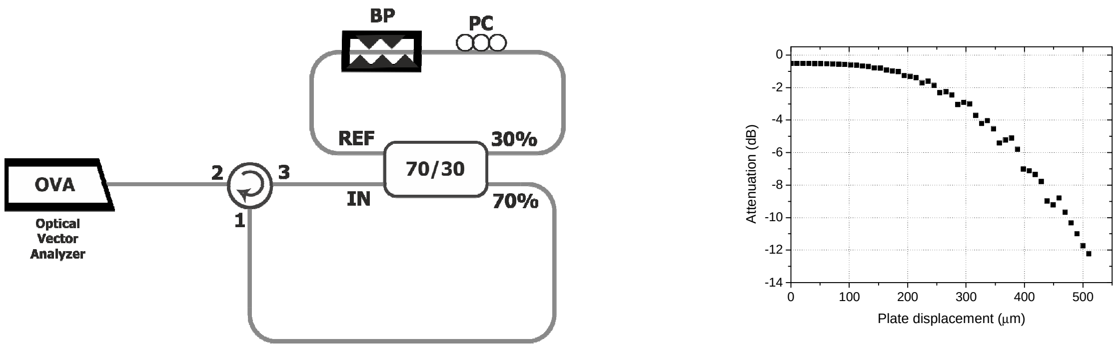


(a) (b)

Fig. 2: Phase, modulus and group delay response vs. frequency for different attenuation values within a 1.59 meter fiber resonator, κ=0.7 (≈1.55 dB): (a) 1 dB attenuation in the loop; (b) 2 dB attenuation in the loop.

3. EXPERIMENTS

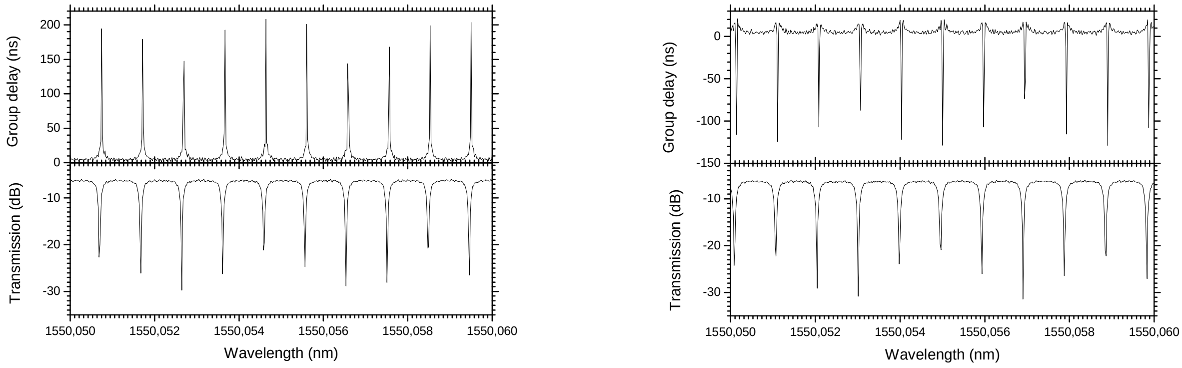
To confirm the previous theoretical analysis, we developed a simple experiment. We constructed the structure of Figure 3(a) with a fiber coupler, a polarization controller and a precision mechanic attenuator based on stress-inducing plates, similar to the one used in [10] (labeled BP in the Figure). The attenuation in the ring is varied by controlling the displacement of the plates through a precision actuator. The attenuation response induced by the plates on the fiber is plotted in Figure 3(b). The total length of fiber in the loop is ~1.59 meters, and the coupler used had a 70% coupling ratio (κ=0.7). An Optical Vector Analyzer (OVA) was used to measure the transmission and group delay response of the structure. Since the OVA is only adapted to measure in reflection, an optical circulator was used to transform transmission into reflection.



(a) (b)

Fig. 3: (a) Experimental setup. BP: Benting Plates; PC: polarization controller. (b) Attenuation induced by the plates as a function of the displacement.

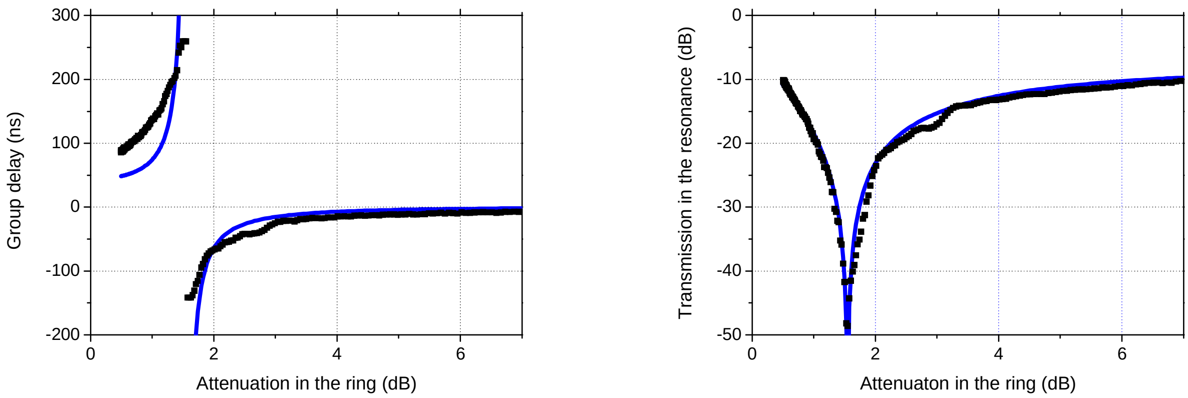
Figure 4 shows two sample transmission and group delay spectra obtained for different attenuation values. The central wavelength for the analysis was set at ~1550 nm with 10 pm (1.25 GHz) measuring span. The separation between peaks (Fig. 3(a) and (b)) corresponds to ~130 MHz which confirms the ~1.59 m loop length. In Figure 4(a), the attenuation was set at ~1.43 dB, corresponding to the case $a<\kappa$. As expected from the above analysis, this configuration gives positive group delays (slow-light regime), peaking in the resonances. In Figure 4(b) the attenuation was increased until ~-1.7 dB which corresponds to the case $a > \kappa$ (fast light regime). Unlike the response in Fig. 4(a), the peaks show a negative value (~-25 ns mean advancement measured), corresponding to the expected fast-light response.



(a) (b)

Fig. 4: Group delay and power transmission in the ring vs. frequency for different attenuation values within the resonator: (a) ~1.43 dB; (b) ~-1.7 dB.

Figure 5 depicts the (a) group delay and (b) transmission loss in the center of the resonances as a function of the attenuation induced by the plates. The dots are experimental data and the lines correspond to the theoretical expectation obtained from the model developed in section 2. We can see a good agreement between the results obtained with the experimental setup and the theoretical model. At critical coupling (~1.55 dB attenuation marked with a red line in Fig. 5b), the transition between positive group delay and negative group delay is visible (slow-fast-light switch). As it can be seen, this working point shows an enhanced sensitivity and seems attractive for high sensitivity measurements using intensity sensors. In the particular case of the structure demonstrated in this work, the displacement sensitivity close to the critical coupling point exceeds 1 dB/µm. For comparison, this sensitivity value is more than two times the sensitivity achieved in [10] using the same bending plates in an interferometric structure.



(a) (b)

Fig. 5: (a) Measured peak group delay and (b) peak loss as a function of the attenuation induced in the ring. In both cases, the dots correspond to measurements and the lines correspond to the theoretical expectation using the model shown in Section 2.

4. CONCLUSIONS

We have theoretically and experimentally demonstrated a versatile all-fiber structure based on a lossy fiber ring resonator that can be used for sensing a variety of physical magnitudes (displacement, pressure, etc). The group delay and hence the loss sensitivity in the device is easily tuned by changing the attenuation and/or coupling ratio in the ring. Close to critical coupling, the setup can be made extremely sensitive to small variations in loss, in good agreement with the sharp group delay evolution in this region. The sensitivity of any intensiometric fiber sensor can therefore be enhanced with this simple structure. This device could be a basic building block in new slow-light-assisted fiber sensors. Moreover, a good agreement between the theory and the developed experiments is demonstrated.

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