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Investigations on an all-tunable fiber ring resonator

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ABSTRACT

The architecture of an all-tunable optical fiber ring resonator is described in detail in this paper. This architecture has been firstly modeled using an original CAD approach. The simulation results demonstrate a total control of both the absolute frequency and the free spectral range of the final optical resonance comb generated by the optical resonator. The different experimental setups used to characterize the tunable resonator are described and the obtained results proving the concept are also provided.

1. Introduction

Tunability is a desired feature in any optical filter [1]. This also applies to the fiber ring resonator (FRR) case due to the high optical quality factor (Q_{Opt}) that can be obtained and to the simplicity in its fabrication [2]. Indeed, the FRR is a very useful element for many applications as it can be used as a high selectivity add-drop optical filter, a high resolution gyroscope, a fiber laser etc. We can particularly mention the phase noise performance that can be achieved for microwave signals generated by an optoelectronic oscillator (OEO) when a high Q_{Opt} FRR is used as the frequency stability element in the oscillator setup [3]. Besides the importance of achieving high spectral purity for the generated microwaves, the tunability is also greatly desired in OEOs. For that reason, numerous studies have been performed to tune the oscillation frequency in different OEO's architectures [4–6].

Certainly, tuning the FRR's frequency response is possible by changing the resonator's temperature or by using the effect of polarization and birefringence in the resonance loop [7]. On the one hand, the FRR's response to the temperature is too weak and it is also very slow. In a previous work [2], we have performed a detailed study on this matter. It has been found, for example, that the *FSR* response to the temperature in a 20 m-long FRR is equal to $|70\text{Hz}|/\text{K}$. This means that a temperature variation of $\Delta T = 1.4 \times 10^5 \text{K}$ is theoretically required to tune the FRR's frequency response by a full *FSR* ($FSR \approx 10$ MHz in a 20 m-long FRR), which is clearly impractical to achieve. On the other hand, the effect of polarization and birefringence is limited and could be sensitive to external perturbations.

In this paper, we first give a brief description of the FRR and later on we present our theoretical and experimental investigations on a particular architecture of the FRR. This architecture is principally based on the enclosure of a phase shifter and a tunable optical coupler (forming a Sagnac mirror) at the same time in a double coupler add-drop FRR. While some research works studying separately similar architectures were reported in the literature [8–11], to our knowledge, no detailed study has been performed to show the effect of the combination of both the phase shifter and the tunable optical coupler on the double coupler add-drop FRR's response. In the present work, our investigations show that such combination allows a complete tuning of the absolute frequency of the generated final optical resonance comb (ORC) and of its free spectral range (*FSR*) as well. In addition, the results of a study performed on the possibility of tuning independently both of these characteristics of an ORC are also addressed.

2. Fiber ring resonator

The architecture of the double-direct-coupled FRR, considered in our studies, is shown in Fig. 1(a). This FRR is fabricated using two low loss two-by-two directional optical fiber couplers (C_1 and C_2) linked together with a single-mode fiber loop. The resonator generates a transverse single ORC with microwave spacing called *FSR*. The *FSR* is given by $FSR = c/nL$, where (L) the fiber loop length, (n) is its refractive index and ($c \sim 3 \cdot 10^8$ m/s) is the light speed in

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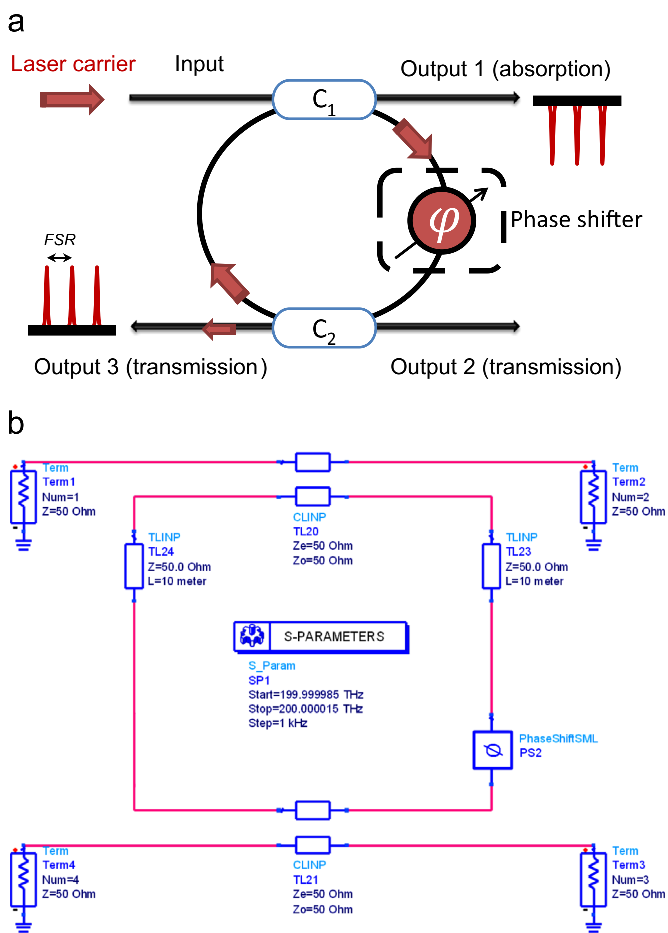

Fig. 1. (a) Architecture of the double-direct-coupled FRR (a phase-shifter is inserted to control the phase delay inside the FRR's loop). (b) ADS model of the FRR.

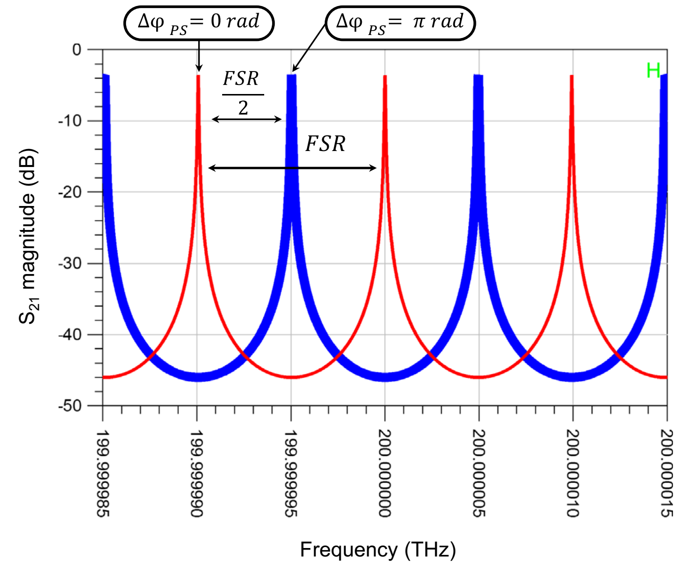

Fig. 2. Transmission spectrum at the third output of a 20 m-long FRR simulated, using an ADS model, while changing $\Delta\varphi_{PS}$'s value by π rad. An absolute frequency shift of the ORC by one half of the *FSR* is obtained.

free space. The Q_{Opt} of this resonator particularly depends on the couplers' coupling coefficients (κ_1 for C_1 and κ_2 for C_2) and on the overall losses in the resonator architecture: couplers' excess loss ($\gamma_{1,2}$), splices' loss (α_s) and fiber linear loss (α_f).

3. Absolute frequency tuning using an optical phase-shifter

As already reported in Ref. [8], it is possible to tune the absolute frequency of an ORC generated by a FRR by inserting an optical phase-shifter (PS) within the FRR's loop [see Fig. 1(a)]. The PS enables the control of the phase delay inside the ring loop and, therefore, the control of the phase matching condition. An additional phase-shift added inside the FRR's loop ($\Delta\varphi_{PS}$) will lead to a proportional absolute frequency shift (Δf_{Opt}; f_{Opt} being the optical resonant frequency) in the ORC as follows [8]:

$$\Delta f_{Opt} = \frac{\Delta\phi_{PS}}{2\pi}\frac{c}{nL} = \frac{\Delta\phi_{PS}}{2\pi}FSR$$

From the above relation, we can clearly notice that when an additional 2π rad phase-shift is added to the optical signal inside the FRR's loop, the resonant frequency will shift by one complete *FSR*. In order to simulate the response of such FRR architecture, we have used an upgraded version of a model of the FRR developed in a previous work [12]. This FRR model is based on an original approach using electronic design software (ADS from Agilent), typically used for microwave systems' design. With this FRR's model [depicted in Fig. 1(b)], we have been able to simulate the transmission response of a 20 m-long FRR including a phase-shifter. Consequently, the abovementioned frequency tuning technique has been confirmed by changing $\Delta\varphi_{PS}$ from 0 to 2π while monitoring the FRR's responses (see Fig. 2; For clarity's sake, the presented results are for a change in $\Delta\varphi_{PS}$'s value by π). Furthermore, we have found that such a tuning technique does not modify the FRR's transmission characteristics (insertion loss (*IL*), Q_{Opt}, etc…).

The abovementioned theory on the optical absolute frequency shift has been experimentally confirmed using a narrow linewidth laser and the wavelength scanning technique [13]. This wavelength scanning technique consists of a frequency fine-tuning of a narrow linewidth (~1 kHz) Koheras fiber laser to explore the FRR's ORC by recording the FRR's response on a photodiode followed by an oscilloscope. In our experimental setup, we have used a 23 m-long FRR including a PS (abbreviated by FRR-PS) and a second 20 m-long FRR as a spectator to witness the absolute frequency shift in the FRR-PS's ORC (see Fig. 3). The results are depicted in Fig. 4 and they confirm that when an additional phase-shift $\Delta\varphi_{PS}=\pi$ is added inside the FRR-PS's loop, its ORC shifts by $FSR/2$.

4. Free spectral range tuning using a variable optical coupler

A fiber loop mirror (FLM), or a Sagnac reflector [14], is a device made by connecting the ports on one side of a two-by-two fibered directional optical coupler. This FLM is usually used in its simplest form as a reflecting device [15]. In that case, the input optical signal is split so that two counter-propagating waves are formed in the fiber loop, which then return to recombine (interfere) at the coupler. Since the optical paths for both counter-propagating waves in the loop are the same, the reflectivity of the FLM will be only determined by the coupling ratio of the optical coupler (if the thermal effects and the polarization rotation inside the fiber are disregarded).

In our case, the same effect has been used to tune the ORC's FSR. This has been achieved in a configuration based on a classical FRR architecture including a FLM inside its loop (abbreviated by FRR-FLM). The FLM, of a length L_{FLM}, has been made by connecting the ports on one side of a tunable optical coupler (TC) [see Fig. 5(a)]. A similar architecture to this FRR-FLM has been studied in Refs. [9,10], where analytical expressions have been derived for a tunable single-direct-coupled ring resonator. Also, in Ref. [11], the effect of the Sagnac phase-shift by the rotation of the Sagnac loop