Numerical Investigation of Silicon Nitride-based Frequency Comb in the Radio over Fiber System

(Student Paper)

Shahryar Sabouri [1], Mojtaba Sohrabi [2], Mircea Catuneanu [1], Dirk Plettemeier [2], Kambiz Jamshidi [1]
[1] Integrated Photonic Devices Group, [2] Chair of Radio Frequency and Photonics Engineering,
Technische Universität Dresden Dresden, Germany
e-mail: shahryar.sabouri@tu-dresden.de

ABSTRACT

To generate carriers with high frequencies in the central office, an integrated frequency comb using optical solitons is studied. Both single and double solitons in a silicon nitride microring cavity are investigated numerically for this purpose. The parameters required for the single solitons with the frequency spacing equal to the resonator free spectral range (FSR) and power suppress ratio of -2dB and double solitons with the frequency spacing of multiple (1-3) resonator FSR and power suppress ratio of -1dB is obtained.

Keywords: Solitons, Silicon nitride, Radio over Fiber, Photonic integrated circuits.

1. INTRODUCTION

Radio-over-Fiber (RoF) technique is a promising solution to distribute data for base stations [1,2]. The main advantage is the possibility to transmit the modulated RF signal over optical fibers with link lengths of several kilometers from Central Office (CO) to the Base Station (BS) (Fig. 1a). Moreover, to generate high-frequency signals (60 GHz and beyond), it has been believed that photonic devices can be better candidates than the conventional electrical techniques because of lower cost and impairments like phase noise [3]. In the central office (CO) of a RoF system, generating a high-frequency carrier signal (60 GHz and beyond) by optical means requires a modulator and RF signal source (see Fig. 1c). In terms of bandwidth, however, a dual-electrode Mach Zehnder modulator has some limitations and signal/carrier generation in a spacing of 60 GHz is not easily achievable [4]. In order to increase the frequency of the carrier signal even further, several methods can be used, including frequency combs. In this paper, we study the formation of stable Kerr comb solitons based on a silicon nitride microring cavity (Fig. 1b). The optical spectrum of such stable solitons provides a train of frequency lines with a spacing more than 60 GHz suitable for BS working in this frequency such as [5]. As it is shown in Fig.1c (bottom), by filtering the intended line through the train of lines in the generated comb, the carrier will be generated in the desired frequency.

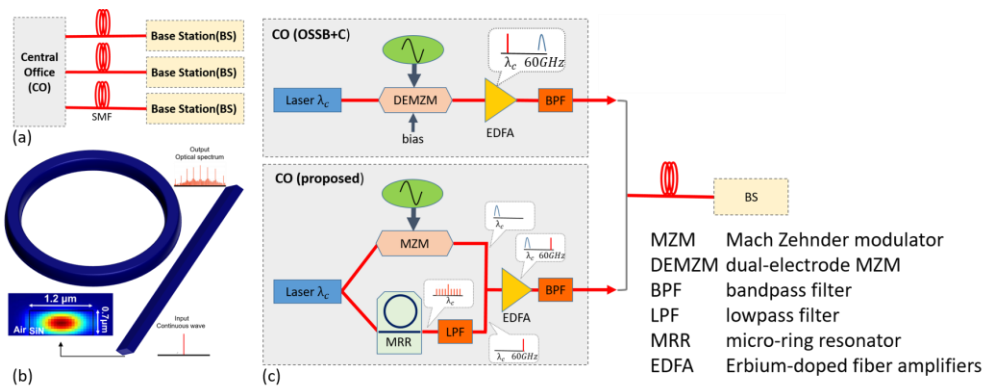


Figure 1. a) Schematic view of a RoF system. b) The studied silicon nitride microring cavity to generate comb frequency lines. C) The Central Office (CO) of a RoF system represented by [2] (top) and proposed in this paper (bottom).

2. SOLITON-BASED KERR COMB MODEL

In order to generate a frequency comb in an integrated photonic circuit, a microring resonator is needed. The input signal, which is a continuous wave generated by a tunable laser, is coupled from the bus waveguide into the microring. The radius of the ring cavity defines the free spectral range (FSR) of the optical spectrum. The intended line spacing in the output-spectrum could be a multiple of the engineered FSR [6, 7]. Single FSR spacing can be

achieved when a single soliton forms in the ring cavity. Soliton refers to an optical field that travels without distortion during propagation due to the balance between nonlinear and dispersive effects in the medium [8]. Once the soliton is formed, it keeps its stability, shape, and power.

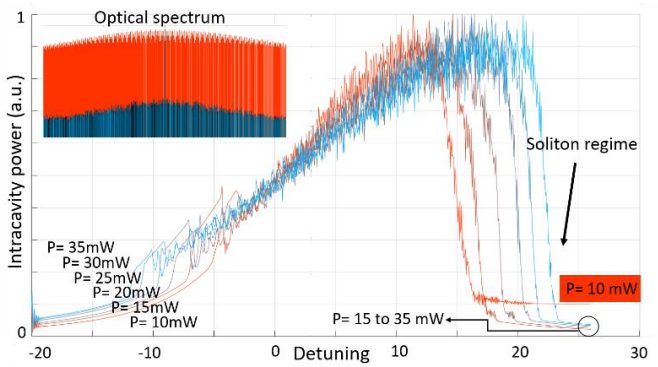


Figure 2. The detuning vs intracavity power for different laser input power. The optical spectrum after detuning is presented.

In this paper, the aim is to get stable soliton where we can have a train of frequency lines spacing more than 60 GHz. To satisfy this, the intracavity field must be studied. Lugiato Lefever equation (LLE) models the intracavity field which is influenced simultaneously by nonlinearity, dispersion, and loss:

$$\frac{\partial\psi}{\partial\tau} = -(1+i\alpha) + i|\psi|^2\psi - i\frac{\beta}{2}\frac{\partial^2\psi}{\partial\theta^2} + F \tag{1}$$

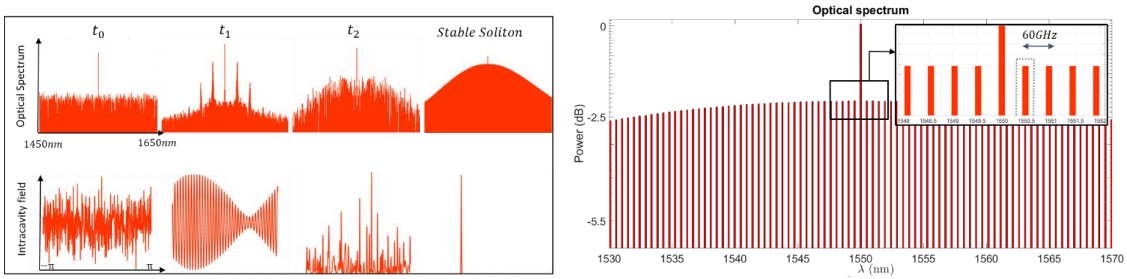
where ψ is the intra-cavity field, α describes the normalized wavelength detuning, β refers to dispersion, F is the normalized pump field intensity, θ is the angular vector of the cavity, and τ is the dimensionless time[6]. We have numerically investigated the formation of the desired soliton in LLE by considering the input power and detuning of the laser.

3. RESULTS

First, the required parameters to obtain solitons in a cavity have to be found. The detuning must be stopped in the soliton regime (upper branch of the bistability curve [9]). However, one can be in the soliton regime but no soliton is formed in the output. That's because of the second parameter to be considered: input power. As it is shown in Fig. 2, all detuning stop in the soliton regime, but only for the power of around 10 mW, the soliton is formed in the cavity.

3.1 Single Soliton

To get a single stable soliton, an input power of 9.7 mW is needed. Figure 3a shows the transient formation of the single soliton into the cavity for a large spectrum. At the beginning (t_0), only the input pump power is observed. At t_1, secondary and higher orders of the comb line are generated through the nonlinearity interactions into the ring: self-phase modulation (SPM), cross phase modulation (XPM), four-wave mixing (FWM), and modulation instability. Finally, all the mentioned nonlinearity mechanisms and dispersion compensate each other and reach an equilibrium, where the single stable soliton is formed. As the FSR of the microring is around 60 GHz, the optical spectrum is scaled in Fig. 3b, where the lines are located in the equidistant spacing of 1×FSR (60 GHz or 0.48 nm). The very first lines have approximately similar power (about 2dB less than the pump power). By filtering each of these lines (based on the required bandwidth), the stable carrier can be obtained.

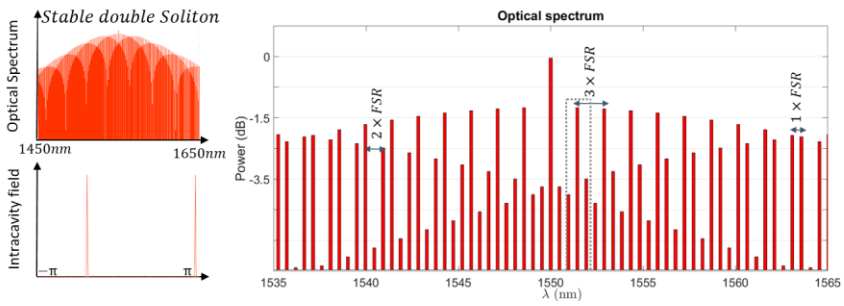


(a) (b)

Figure 3. a) The transient formation of a single soliton (Intra field cavity and its spectrum). b) The optical spectrum of the ring cavity in the range of 40nm. The spacing of the comb lines is 60GHz or 0.48 nm.

3.2 Double Soliton

In a microring cavity, under proper conditions, more than one soliton can exist. In the above-mentioned structure, for instance, only by decreasing the power to 8.5 mW, the second soliton can be formed. Both solitons remain stable and keep their waveform within the microring cavity (Fig. 4a-bottom). The advantage of this multi-soliton field is that in the frequency domain, their optical spectra overlap and provide an alternative form of frequency comb (Fig. 4a-top). Figure 4b shows the possibility of filtering carriers at different distances: 1-3×FSR (60-180 GHz). Comparing the single soliton spectrum, however, the power of the first line close to the central frequency is much less. On the other hand, to generate carriers with higher frequency, a double soliton is a better option where the power of a line in a distance of 3×FSR is only 1 dB less than the pump power (see Fig. 4b).



(a) (b)

Figure 4. a) Intra field cavity and its spectrum. b) The optical spectrum of the ring cavity in the range of 40nm. The spacing of the comb lines is 60GHz or 0.48 nm.

4. CONCLUSIONS

In order to generate carriers with high bandwidth (>60 GHz) to be used in the central office in a Radio over Fiber system, a frequency comb based on integrated photonic devices has been employed. A silicon nitride microring cavity has been designed to provide an FSR of about 60 GHz. We have numerically modelled and studied the intracavity field under nonlinear Kerr effect, to investigate the formation of stable solitons. The laser detuning and power have been studied to obtain a stable single-soliton and a double-soliton. In terms of single-soliton, the frequency spacing with 1×FSR and power suppress ratio of -2 dB and for double-soliton, the frequency spacing of multiple FSR and power suppress ratio of -1 dB is obtained.

ACKNOWLEDGEMENTS

This work is supported in part by the German Research Foundation (DFG) in the context of the “Silicon-on-insulator based integrated optical frequency combs for microwave, THz and optical applications” project.

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