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Generator Systems for Optical Subcarriers Based on Ring Resonator in Series and Parallel with Phase Modulation

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Abstract— This work presents four systems for generation of optical subcarriers in the C-band in optical communications, based on serial and parallel amplified optical ring resonator with phase modulation and 10 GHz spectral spacing between subcarriers. The systems were numerically simulated and were able to generate between 83 to 145 subcarriers with output power levels of -5 to 26 dBm for an input power of 0 dBm and with flatness of 1.4 to 8 dB with a minimum OSNR of 30 dB.

Index Terms— optical loop, phase modulator, subcarrier generator.

I. INTRODUCTION

An ongoing challenge for engineers and operators of optical networks based on Dense Wavelength-Division Multiplexed (DWDM) is to adapt the existing telecommunications infrastructure to the growing demand for data services from the Internet [1]. Flexibility, scalability, and efficiency are therefore paramount for optical networks in the future. Accordingly, elastic optical networks (EONs) have emerged as a promising candidate since they use spectrum more efficiently than DWDM-based optical networks [2].

Based on Orthogonal Frequency Division Multiplexing (OFDM), the EON allocates spectrum efficiently [3]–[6]. One of the important subsystems within this optical network is the bandwidth variable transponder (BVT). A BVT can be used to adjust the bandwidth of an optical subcarrier by adjusting the transmission bit rate or modulation format [2]. It is possible to use multiple lasers to create a set of subcarriers for a BVT. However, this is not cost-effective since each subcarrier would need a laser.

Thus, another method for generating subcarriers would be through optical frequency comb (OFC) techniques [7]. An OFC is formed by a series of uniformly spaced spectral components. One type of OFC generator is the use of semiconductor and fiber-based mode-locked lasers (MLLs) [8]–[13]. Another technique to generate optical subcarriers is to use a fiber optic recirculation (feedback) loop [14]–[18]. In this technique, a modulator is used to generate sidebands from the optical signal provided by a single laser source. Each time the optical signal passes through the modulator, a frequency comb consisting of a few lines is generated. Thus, with multiple passes through the modulator, the sidebands generate their own lines and cause a broadening of the OFC until the system reaches its steady state.

The recirculation loop effect can also be enhanced by using highly nonlinear fibers and dispersion compensated fibers or other nonlinear media, such as semiconductor doped optical amplifier (SOA) or erbium amplifier doped fiber (EDFA), to increase the number of lines in the loop. In this case, four-wave mixing (FWM) is the important nonlinear effect for this process [19].

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Therefore, based on [16], three optical frequency comb generators using phase modulation in a cascaded amplified circular loop in series and parallel are presented in this paper.

This work has been organized as follows: Section II describes the optical setup for each of the three systems proposed for the generation of optical subcarriers; in Section III, we describe the methodology used for the numerical simulation of each of the systems described in Section II and, moreover, we analyze the numerical results obtained and compare them with similar systems presented in the literature; finally, in Section IV the conclusions are presented.

II. OPTICAL SYSTEMS

First, we describe the OFC system (System I) proposed in [16] since the three systems proposed in this work are based on it. System I will also be used as a reference system in comparison to the proposed systems and those existing in the literature regarding the following performance parameters: number of subcarriers generated, flatness and optical noise-signal ratio (ONSR).

The System I is shown in Fig. 1(a) and uses a balanced four-port beamsplitter (BS^1), having two interconnected bottom ports through a single-mode fiber (SMF) with an erbium doped fiber amplifier (EDFA) cascaded with a phase modulator (PM), forming an amplified and phase-modulated circulating (APMC) loop.

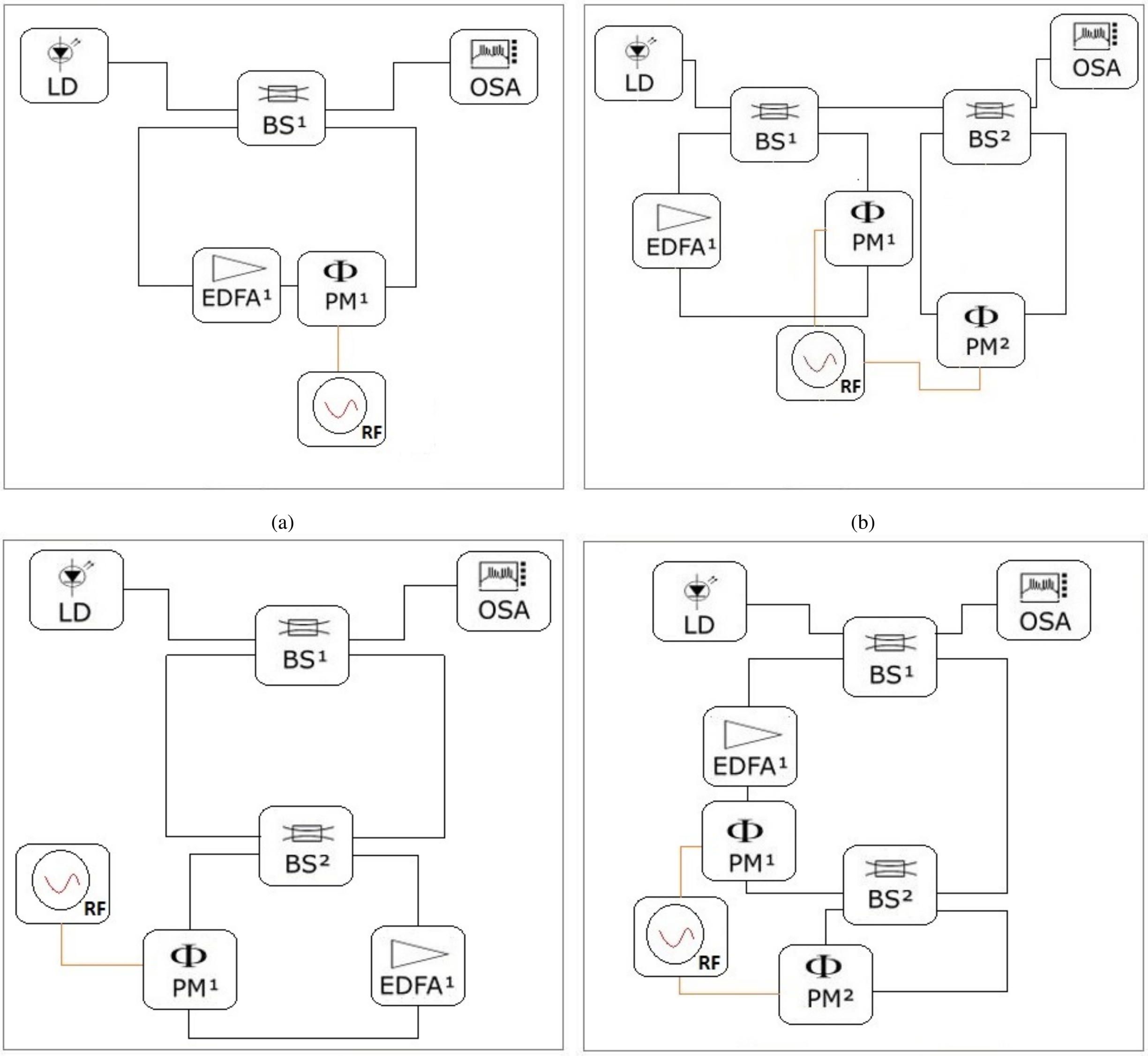
In Fig. 1(a), the continuous-wave (CW) signal generated by a laser diode (LD) is split into two after passing through the BS^1, one half of the optical signal passes through the upper output port 1 of the BS^1 and is detected by the optical spectrum analyzer (OSA), while the other half of the signal enters the optical loop through the lower output port 2. This signal is amplified and modulated in phase by a 10 GHz sinusoidal RF signal. After that, the modulated signal interferes with the signal emitted by LD and is detected in the OSA. The EDFA, in the APMC loop, boosts the signal to nearly compensate for the loop losses.

The first proposed system (System II), shown in Fig. 1(b), consists of two circulating loops in series, and the second loop is not amplified, but only modulated in phase (PMC loop). In Fig. 1(b), has a second beamsplitter (BS^2) forming a second PMC loop. Similar to System I, the two lower ports of the BS^2 are used to form an optical circulating loop that, in that case, contains only one phase modulator. Such that, the signal in BS^2 is modulated again in phase by the same sinusoidal RF signal applied in first loop. And this process of double interference (in BS^1 and BS^2) in series is repeated indefinitely.

The second proposed OFC generator (System III) is shown in Fig. 1(c). This system is formed by two circulating loops in parallel and connected by a BS (BS^2). The outer loop of this optical setup is an APMC loop. The optical signal emitted by the LD circulates clockwise in the inner loop and counterclockwise in the APMC loop on System III.

The last proposed system, System IV, works in a similar way to System III. System IV, as shown in Fig. 1(d), also consists of two circulating loops, where the inner loop is an APMC-type loop and the outer loop includes only one PM. Both PMs are driven by the same RF.

System I has the lower complexity of optical hardware compared to the other proposed systems, therefore, it is able to model mathematically the electrical output field E_{out} of the system shown in Fig. 1(a) from the electric field E_0 emitted by the LD using the Jacobi-Anger expansion, which gives us the shape of the subcarrier harmonics [10], as shown below:



(a) (b)

(c) (d)

Fig. 1. Optical setups of the proposed systems for generating optical subcarriers (DL - laser diode, BS - beamsplitter, PM - phase modulator, EDFA - erbium doped fiber amplifier, OSA - optical spectrum analyzer, RF: radio frequency generator frequency). a) Optical setup of the System I, b) Optical setup of the System II, c) Optical setup of the System III, d) Optical setup of the System IV.

$$E_{out}(t) = E_0 e^{j2\pi f_c t} e^{j\pi R sin 2\pi f_s t} = E_0 \sum_{n=1}^{\infty} \gamma^n J_n(\pi R) e^{j2\pi(f_c + n f_s)}, \tag{1}$$

where: $J_n(\pi R)$ is a Bessel function of n-order, R is the rate of the RF signal for half wave, f_c is carrier frequency, f_s is sampling frequency of the RF and γ is the gain introduced by EDFA.

Table I shows the parameters used in the four systems. The optical components of the System I are interconnected with an SMF of 30 cm length and in the System II with an OF of 45 cm. The BS's in both inner loops from Systems III and IV are interconnected with SMF of 20 cm in length, while the optical outer loop has a total length of 40 cm.

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TABLE I. PARAMETERS USED IN THE NUMERICAL SIMULATIONS.

Components	**Parameters**
Laser (LD)	Optical Power: 0 dBm
	Frequency: 193.1 THz
	Linewidth: 100 kHz
Beamsplitter (BS)	Coupling coefficient: 0.5
Phase modulator (PM)	RF: 10 GHz
EDFA System I	Foward pump power: 10 mW
	length: 3 m
EDFA System II	Foward pump power: 10 mW
	length: 3 m
EDFA System III	Foward pump power: 15 mW
	length: 3 m
EDFA System IV	Foward pump power: 20 mW
Single mode fiber (SMF)	length: 3 m
	Attenuation: 0.2 dB/km

III. METHODOLOGY AND RESULTS

The four systems, one reference system (System I) and three proposed systems (System II-IV), were numerically simulated using the *OptiSystem*© software [20]. For each system, 400 iterations were performed, due to the optical loops, and the last 100 samples of the signal were captured in the OSA as a function of the power level (dBm) and wavelength (nm).

The following parameters were used to analyze the performance of the proposed systems in relation to the reference system and the systems presented in [12], [15] and [21]: number of subcarriers generated, minimum flatness of 5 dB and minimum ONSR of 30 dB. ONSR was defined as the difference between the average power output of each system and the average background power of the OFC generated. Thus, the average background power that was used as a reference for the first two systems (System I-II) was approximately -60 dBm, while for the last two systems (Sistem III-IV) were around -10 dBm and -50 dBm, respectively. Figure 2 shows the behavior output average power as a function of wavelength for each of the four systems.

Figure 2(a) shows that System I was able to generate from 96 to 141 subcarriers with average power per peak of 0 dBm and -2 dBm, respectively, spaced at regular intervals of 10 GHz and total bandwidth around 1.18 THz. System I obtained a flatness of 2.4 and 3.4 dB for an OSNR of 50 and 48 dB, respectively, while in Fig. 2(b) it is observed that System II generated 83 and 89 subcarriers with flatness of 3.3 and 8.0 dB for an OSNR of 60 and 55 dB, with an average output power of 0 and -5 dBm, respectively. The numerical results obtained for System I and System II, respectively, are shown in Table II and Table III.

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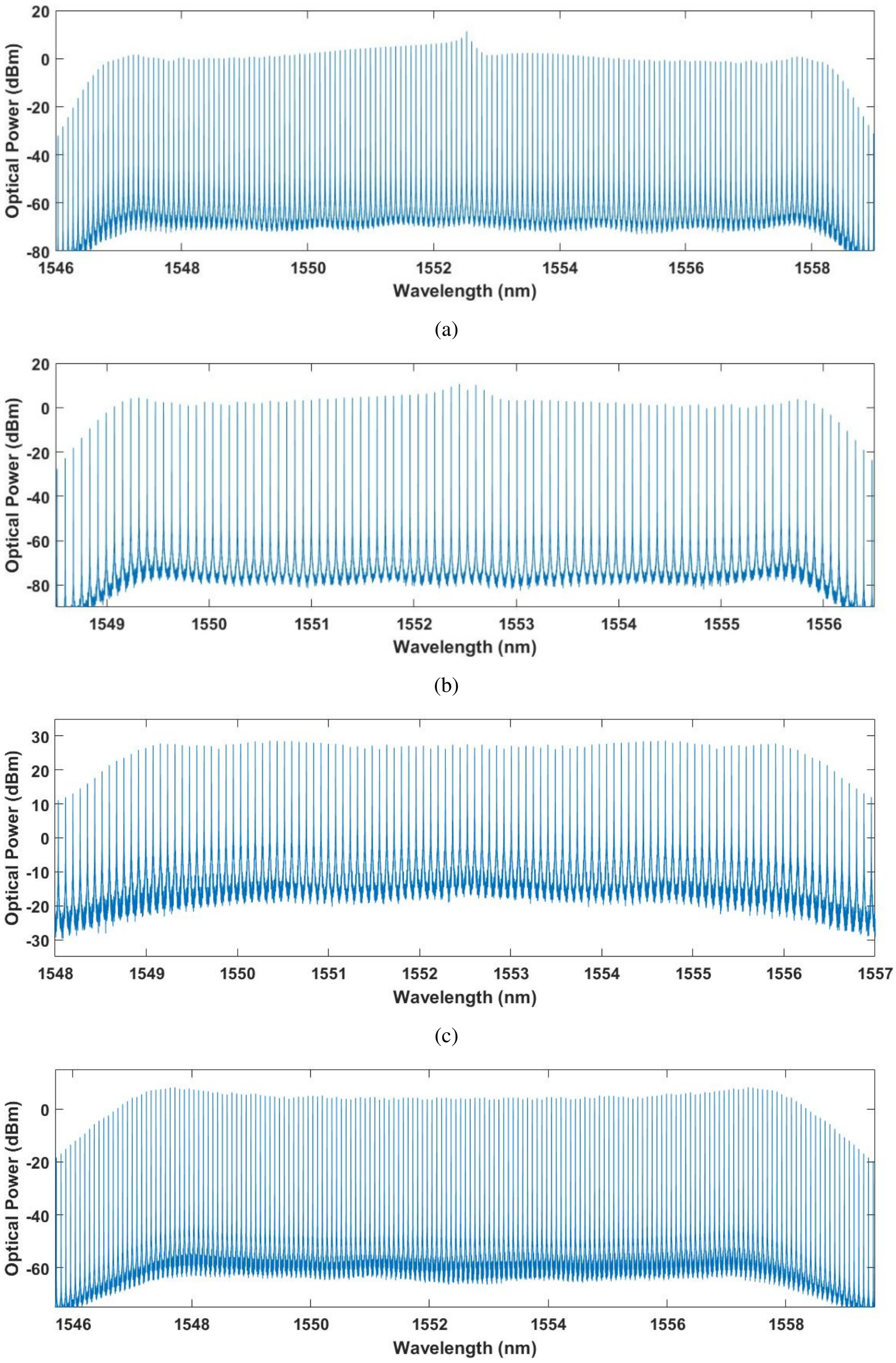

(d)

Fig. 2. Average output power versus wavelength. (a) Systems I: OFC of 96 and 141 subcarriers with flatness of 2.4 and 3.4 dB and OSNR of 50 and 48 dB for output average power of 0 and -2 dBm, respectively; (b) System II: OFC of 83 and 89 subcarriers with flatness of 3.3 and 8.0 dB and OSNR of 55 and 60 dB for output average power of -5 and 0 dBm, respec -tively; (c) System III: OFC of 89 and 95 subcarriers with flatness of 1.4 and 4.2 dB and OSNR of 35 and 40 dB for output average power of 26 and 23 dBm, respectively; and (d) System IV: OFC of 139 and 145 subcarriers with flatness of 2.1 and 5 dB and OSNR of 45 to 50 dB for output average power of 3 and 0 dBm, respectively.

In Fig. 2(c), System III was able to generate 89 to 95 subcarriers, equally spaced by 10 GHz, with flatness from 1.4 to 4.2 dB for an OSNR of 35 to 30 dB. The numerical results obtained for System III are described in Table IV. The occupied total bandwidth by OFC was from 890 GHz to 950 GHz.

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System IV, as shown in Fig. 2(d), was able to generate 139 to 145 subcarriers with a flatness from 2.1 to 5.0 dB, respectively, as shown in Table V. The occupied total bandwidth by OFC was from 1.39 THz to 1.45 THz.

If we compare the results obtained from the three proposed systems (System II-IV) as the reference system (System I), as shown in Tables II-V, we can conclude: (1) System IV was the most efficient in terms of the number of subcarriers generated, (2) System III had the lowest flatness; (3) and System II obtained the highest ONSR.

TABLE II. NUMERICAL RESULTS OBTAINED FROM SYSTEM I.

Power (dBm)	**Subcarries**	**Flatness** (dB)	**OSNR (dB)**
0	96	2.4	50
-2	141	3.4	48

TABLE III. NUMERICAL RESULTS OBTAINED FROM SYSTEM II.

Power (dBm)	**Subcarries**	**Flatness (dB)**	**OSNR (dB)**
0	83	3.3	60
-5	89	8.0	55

TABLE IV. NUMERICAL RESULTS OBTAINED FROM SYSTEM III.

Power (dBm)	**Subcarries**	**Flatness (dB)**	**OSNR (dB)**
26	89	1.4	35
23	95	4.2	30

TABLE V. NUMERICAL RESULTS OBTAINED FROM SYSTEM IV.

Power (dBm)	**Subcarries**	**Flatness (dB)**	**OSNR (dB)**
3	139	2.1	50
0	145	5	45

Table VI shows a comparison among the OFC generation systems in [12], [15] and [21] with the proposed systems in relation to the number of subcarriers generated, flatness and ONSR.

Systems I, III, and [12] use only one PM. However, Systems I and III have a greater number of subcarriers and less flatness than [12]. The system in [21] has a greater number of subcarriers compared to Systems I, II and III, but it has higher flatness and lower OSNR compared to the systems proposed by this work. In addition, the systems presented by [15], [21] use LDs with a power of 14.5 dBm and 11 dBm respectively, both more powerful than those presented in our work (0 dBm). System IV was able to generate more subcarriers than all the systems analyzed.

TABLE VI. COMPARATIVE AMONG OFC GENERATING SYSTEMS.

Generator	Input power	Subcarries	Subcarrier spacing	Flatness	OSNR
System I	0 dBm	96	10 GHz	2.4 dB	50 dB
System II	0 dBm	83	10 GHz	3.3 dB	60 dB
System III	0 dBm	89	10 GHz	1.4 dB	35 dB
System IV	0 dBm	139	10 GHz	2.1 dB	50 dB
[21]	14.5 dBm	113	25 GHz	5.0 dB	26 dB
[15]	11 dBm	30	20 GHz	-	-
[12]	0 dBm	29	10 GHz	5 dB	-

IV. CONCLUSIONS

In this work, four systems were analyzed numerically for the generation of optical subcarriers based on serial and parallel optical loops with phase modulation for C-band in optical communications. The proposed systems can obtain dozens of subcarriers, spaced at regular intervals of 10 GHz, with frequency spacing controlled by a precise radio-frequency oscillator. The reference system (System I) was able to generate 96 and 141 subcarriers with flatness of 2.4 and 3.4 dB and OSNR of 50 and 48 dB. System II generated 83 and 89 subcarriers for 3.3 and 8.0 dB flatness with OSNR of 60 and 55 dB. In System III, 89 and 95 subcarriers were generated with a flatness of 1.4 to 4.2 dB and OSNR of 35 to 30 dB. In System IV, it was able to reach 139 to 145 subcarriers with flatness of 2.1 to 5 dB and OSNR of 50 and 45 dB. In comparison with other systems in the literature, the three systems proposed had the following advantages: less complexity of optical hardware for implementation, more subcarriers generated and high OSNR.

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