

Article

Concurrent Third-Order Replicas in an Electro-Optical SOA1_SOA-MZI_SOA4 Cascade via Four-Wave Mixing and Cross-Phase and Cross-Gain Modulation

Hassan Termos ^{1,2} ¹ APEX Technologies, 91460 Marcoussis, France; hassan.termos@icfo.eu² ICFO—The Institute of Photonic Sciences, 08860 Castelldefels, Barcelona, Spain

Abstract

Concurrent up- and down-frequency conversion is central to radio-over-fiber (RoF) and millimeter-wave (MMW) system design. However, existing all-optical mixers based on semiconductor optical amplifiers (SOAs) typically exploit a single nonlinear mechanism, such as four-wave mixing (FWM), cross-gain modulation (XGM), or cross-phase modulation (XPM), and therefore generally provide several frequency conversions. Their performance is further constrained by the available mixer bandwidth and by noise contributions from sampling, thermal, and shot noise. Combining multiple such mechanisms in cascade to concurrently generate both up- and down-mixed replicas at GHz-range frequencies has, to our knowledge, not previously been demonstrated. We address this by proposing and experimentally validating a three-stage electro-optical architecture, denoted SOA1_SOA-MZI_SOA4, combining two single SOAs (SOA1, SOA4) with an SOA-based Mach–Zehnder interferometer (SOA-MZI) to generate concurrent third-order replicas through sequential FWM, XPM, and XGM interactions. In the first stage, FWM at the SOA1 output generates third-order components; in the second, these are further processed by XPM-XGM within the SOA-MZI; in the third, the resulting signal is amplified at the SOA4 output. Measured electrical spectra confirm the simultaneous up- and down-conversion of the third-order signal at each stage, reaching a conversion efficiency of up to 14 dB at 15 GHz. These results show that concurrent third-order up- and down-mixing, combining FWM, XPM, and XGM in a single cascaded architecture, is achievable with potential application in high-frequency electro-optical signal processing.

Keywords: electro-optical concurrent up- and down-mixing; four-wave mixing; cross-phase modulation; cross-gain modulation; semiconductor optical amplifier Mach–Zehnder interferometer



Academic Editor: Davide Rocco

Received: 21 August 2026

Revised: 12 September 2026

Accepted: 20 September 2026

Published: 22 September 2026

Copyright: © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The terahertz (THz) and millimeter-wave (MMW) regions of the electromagnetic spectrum have attracted growing interest in their wide range of applications, motivating the development of mixing devices capable of generating high-power radiofrequency (RF) pulses up to 1.5 THz [1–6]. Radio-over-fiber (RoF) technology, with its low-loss transmission and broad bandwidth, is a key enabler for such systems, supporting applications including wireless fidelity (Wi-Fi), surveillance radar, and cellular and satellite communications [7].

Up- and down-mixing are central to RoF and MMW system design. Concurrent mixing has been implemented using a variety of electro-optical mixers, including electro-optic

modulators (EOMs) [8], electro-absorption modulators (EAMs) [9], and photodiodes [10,11]. All-optical frequency mixing offers an alternative route, exploiting the intrinsic nonlinearities of semiconductor optical amplifiers (SOAs) through cross-gain modulation (XGM) [12] and four-wave mixing (FWM) [13,14]. Among these, the SOA-based Mach–Zehnder interferometer (SOA-MZI) is particularly attractive, as its cross-phase modulation (XPM) nonlinearity enables simultaneous frequency conversion [15–23], which makes it a valuable building block for RF communication and MMW systems. Beyond frequency conversion, the SOA-MZI can also serve as an active element for optical signal generation and all-optical gating [24–37]. By incorporating the SOA-MZI into an optical feedback cavity, different laser configurations can be realized, including ring, linear, and Fabry–Pérot-type cavities, where the SOA provides the required optical gain [38–56]. The nonlinear interferometric response of the SOA-MZI can further enable optical switching and gating, providing control over the generated optical signal. Thus, the SOA-MZI offers a versatile platform that can combine laser light generation, optical gating, and simultaneous frequency conversion within a single photonic architecture.

FWM-based frequency generation in an SOA arises from the nonlinear interaction between an optical intermediate-frequency (IF) signal and an optical local-oscillator (LO) signal, governed by three mechanisms. Carrier density modulation (CDM), referring to gain and refractive-index fluctuations induced at the beat frequency of the input signals, is set by the SOA carrier lifetime, which reflects interband transitions between the conduction and valence bands; it dominates at low detuning frequencies (below a few GHz). At higher detuning, spectral hole burning (SHB) and carrier heating (CH) take over: SHB arises from the redistribution of carriers within the gain spectrum, while CH results from stimulated emission and free-carrier absorption, both of which modulate the carrier population and, in turn, the optical gain. Because SHB and CH are intraband effects, they occur on sub-picosecond timescales (~ 100 fs), allowing efficient FWM generation at frequencies above a few GHz [57,58].

Beyond these intrinsic mechanisms, SOA nonlinearities support all-optical mixing across a broad range of applications [59]. Frequency conversion can also be achieved by driving the electrical port of a single SOA or of the SOAs within an SOA-MZI: modulating the carrier density in either arm directly modulates the photonic gain, which lends this approach considerable flexibility [23]. Its bandwidth is nonetheless limited by the optical mixer itself, particularly in SOA-MZI configurations, and is further constrained by sampling noise, which attenuates harmonics and signal replicas, as well as by thermal noise, shot noise, and aliasing, all of which can degrade signal integrity and overall system performance.

In this work, we present an approach for generating concurrent up- and down-mixed third-order replicas using a cascaded electro-optical SOA1_SOA-MZI_SOA4 architecture, based on the combined nonlinear interactions of FWM, XPM, and XGM. Input signals at 5 dBm and wavelengths of 1560 nm and 1565 nm are applied to SOA1, whose FWM nonlinearity generates third-order up- and down-mixed replicas at its output. In the second stage, these FWM-generated replicas undergo further frequency conversion within the SOA-MZI via XPM-XGM interactions, providing additional control over the resulting spectral components. In the third stage, the replicas are amplified at the SOA4 output. To our knowledge, this is the first application of combining FWM-XPM-XGM interactions to third-order mixing in a cascaded SOA1_SOA-MZI_SOA4 configuration. We verify the resulting up- and down-mixed signal generation experimentally through electrical spectra measured at each stage, together with an evaluation of conversion efficiency, and discuss potential applications in wireless access [60] and MMW systems.

2. Performance Analysis of Concurrent Third-Order Up- and Down-Mixing in an Electro-Optical SOA1_SOA-MZI_SOA4 Design

2.1. Electro-Optical Concurrent Mixing Setup

Figure 1 illustrates the experimental setup for simultaneous electro-optical up- and down-conversion utilizing the SOA1_SOA-MZI_SOA4 architecture [22,61]. The fundamental properties and mixing characteristics of the SOA-MZI have been extensively studied in prior research [62]. In this setup, the RF signal at a wavelength of $\lambda_{RF} = 1560$ nm is injected into SOA1 through its electrical interface. The modulation of SOA1 is controlled by the combination of a bias current and the RF signal, which ensures precise operation. The bias current of SOA1 is set to 600 mA, while the electrical ports of the SOAs are configured with a $50\ \Omega$ impedance. A second RF generator (Gen2), operating at $f_{RF} = 6$ GHz, modulates the RF signal based on its intensity. The incoming RF power is adjusted to 13 dBm at the input of the second Mach–Zehnder modulator (MZM2), with an average optical power of 5 dBm, corresponding to -20 dBm in the electrical domain, which is critical for conversion efficiency (CE) calculations.

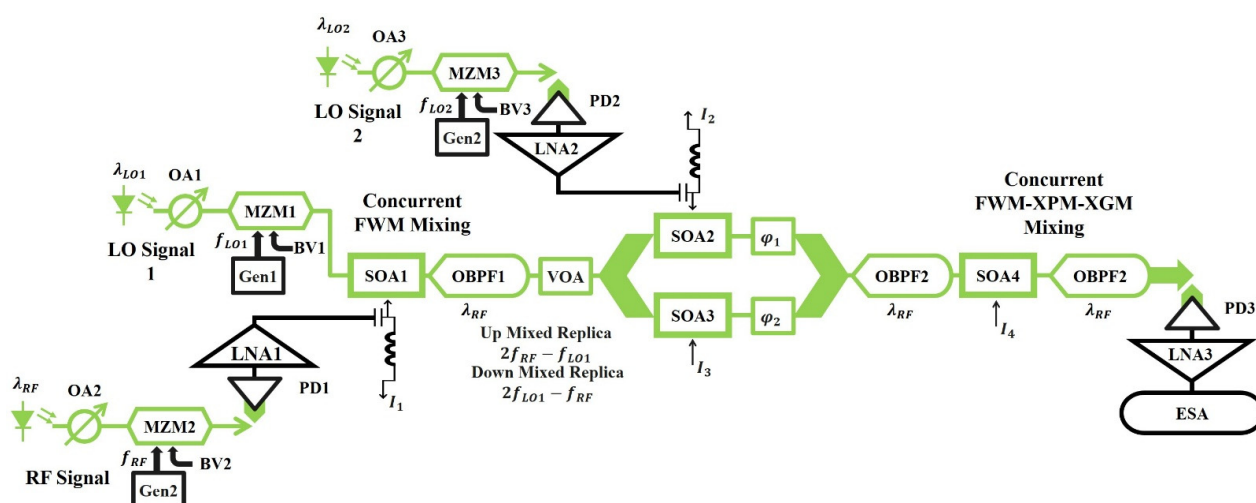


Figure 1. Concurrent electro-optical up- and down-mixing setup dependent on the combination of FWM-XPM-XGM effects in the cascaded SOA1_SOA-MZI_SOA4 design. ESA: electrical spectrum analyzer, FWM: four-wave mixing, Gen: generator, LO: local oscillator, LNA: low-noise amplifier, MZM: Mach–Zehnder modulator, OA: optical attenuator, OBPF: optical band-pass filter, PD: photodiode, RF: radio frequency, VOA: variable optical attenuator, BV: bias voltage, XGM: cross-gain modulation, and XPM: cross-phase modulation.

Conversely, the local oscillator (LO) signal, with a wavelength of $\lambda_{LO1} = 1565$ nm and frequency $f_{LO1} = 5$ GHz, is generated by Gen1 and injected into the optical port of SOA1. The LO signal's average power is also 5 dBm. Electro-optical mixing between the RF and LO signals is driven by the FWM effect, leading to the generation of third-order replicas at the SOA1 output, as detailed in Table 1. Notably, FWM emerges as the dominant nonlinear effect as input power increases. To ensure precise FWM mixing and suppress amplified spontaneous emission (ASE), an optical band-pass filter (OBPF) is applied at the SOA1 output, finely tuned to the wavelength of the RF signal.

Consequently, the FWM-mixed signal, incorporating third-order modulation, is introduced into the central port of the SOA-MZI after its incoming power is increased to 10 dBm and subsequently optimized using a variable optical attenuator (VOA). This attenuation ensures the optimal average power required for effective mixing within the SOA-MZI. A second LO signal, with a wavelength of $\lambda_{LO2} = 1570$ nm and a frequency of $f_{LO2} = 8$ GHz, is injected into the electro-optical gate of the SOA-MZI, with its peak power

set to 5 dBm. Additionally, the bias currents for SOA2 and SOA3 are precisely tuned to 600 mA to maintain optimal operating conditions.

Table 1. Frequency components of the simultaneous electro-optical up- and down-mixing at the SOA1 output based on the FWM nonlinear effects.

Frequency Components (GHz)	
Input SOA1 Ports	$f_{RF} = 6$
	$f_{LO1} = 5$
Output SOA1 Port	$f_{RF} = 6$
	$f_{LO1} = 5$
	$2f_{LO1} - f_{RF} = 4$
	$2f_{RF} - f_{LO1} = 7$

Within the SOA-MZI, the combined effects of XPM and XGM enable the interaction between the FWM signal and the second LO signal, resulting in the generation of new up- and down-mixed replicas at higher frequencies. Consequently, the third-order replicas initially produced at the SOA1 output are further frequency-shifted within the SOA-MZI, as detailed in Table 2. It is important to emphasize that the generation and frequency conversion of third-order modulation constitute the core focus of this study.

Table 2. Frequency components of the simultaneous electro-optical up- and down-mixing at the SOA-MZI output based on the XPM-XGM nonlinear effects.

Frequency Components (GHz)		
Input SOA-MZI Ports		$f_{RF} = 6$
		$f_{LO1} = 5$
		$f_{LO2} = 8$
		$2f_{LO1} - f_{RF} = 4$
		$2f_{RF} - f_{LO1} = 7$
Output SOA-MZI Port	Up-Mixed Replicas	$f_{LO2} + 2f_{LO1} - f_{RF} = 12$
		$f_{LO2} + 2f_{RF} - f_{LO1} = 15$
		$f_{LO2} + f_{LO1} = 13$
		$f_{LO2} + f_{RF} = 14$
	Down-Mixed Replicas	$f_{LO2} - 2f_{LO1} + f_{RF} = 4$
		$f_{LO2} - 2f_{RF} + f_{LO1} = 1$
		$f_{LO2} - f_{LO1} = 3$
		$f_{LO2} - f_{RF} = 2$
	Down-Mixed Replicas	$ 2f_{LO1} - f_{RF} - f_{LO2} = 4$
		$ 2f_{RF} - f_{LO1} - f_{LO2} = 1$
		$ f_{LO1} - f_{LO2} = 3$
		$ f_{RF} - f_{LO2} = 2$

At the SOA-MZI output, the second OBPF (OBPF2) is precisely tuned to the wavelength of the FWM signal, which corresponds to the RF signal wavelength. To enhance the quality of the up- and down-mixed replicas derived from the sampled FWM-XPM-XGM signal, a fourth SOA (SOA4) is introduced, operating with a bias current of 600 mA. The

primary role of SOA4 is to amplify the sampled FWM-XPM-XGM signal by approximately 20 dB, with the amplification level varying based on the frequency of the third-order replicas because the amplification at a higher frequency is higher than the one at a low frequency due to its amplification process. The SOA4 operates purely as an amplifier, providing gain to the signal without any mixing. The amplification process still depends on the current for the carrier injection into the SOA, which enables gain for the input FWM-XPM-XGM signal.

Following amplification, the FWM-XPM-XGM signal is filtered using a third OBPF (OBPF3) to effectively suppress ASE. The refined signal then undergoes a detection process using a uni-traveling carrier photodiode (UTC-PD) [63,64], which ensures a high-speed and low-noise optical-to-electrical conversion. Subsequently, the resulting electrical signal is further amplified by a low-noise amplifier (LNA), which provides an additional 35 dB gain. To comprehensively evaluate the performance of the up- and down-mixed replicas, a detailed spectral analysis is conducted using a high-resolution electrical spectrum analyzer (ESA), specifically the 82407R model from Adler.

Integrating the FWM mixed signal generated by SOA1 with the XPM-XGM mixed signal produced by the SOA-MZI and employing the auxiliary SOA4 for amplification to concurrently generate third-order up- and down-mixed replicas presents a challenging task that demands meticulous synchronization of multiple components. At the output of SOA1, four frequency components are acquired, as outlined in Table 1, resulting from the FWM nonlinear effect within the initial SOA. The input signal at f_{RF} manifests as a down-mixed FWM replica at $2f_{LO1} - f_{RF}$ and an up-mixed FWM replica at $2f_{RF} - f_{LO1}$ at the SOA1 output. These FWM replicas are attained due to the third-order mixing phenomenon in SOA1. It is worth noting that leveraging the swift response time of SOAs [65], we employ ultrafast switching at the picosecond or femtosecond scale in the SOA1_SOA-MZI_SOA4 design, making use of FWM-XPM-XGM interactions.

For the identification of replicas, the application of the basic sampling concept is employed for up-conversion, whereas down-conversion utilizes band-pass sampling [66] at both the SOA-MZI output and the SOA4 output. The output frequency components initially range from $f_{LO2} - 2f_{RF} + f_{LO1} = 1$ GHz to $f_{LO2} + 2f_{RF} - f_{LO1} = 15$ GHz. As outlined in Table 2, there are four up-mixed replicas and eight down-mixed replicas. During the up-conversion process, there are also four replicas corresponding to the down-conversion replicas due to their frequencies aligning with the down-conversion principle. Consequently, the simultaneous FWM-XPM-XGM signal undergoes up-conversion at $f_{LO2} + 2f_{LO1} - f_{RF}$, $f_{LO2} + 2f_{RF} - f_{LO1}$, $f_{LO2} + f_{LO1}$, and $f_{LO2} + f_{RF}$ and undergoes down-conversion at $f_{LO2} - 2f_{LO1} + f_{RF}$, $f_{LO2} - 2f_{RF} + f_{LO1}$, $f_{LO2} - f_{LO1}$, and $f_{LO2} - f_{RF}$. The utmost achieved frequency span is $f_{LO2} + 2f_{RF} - f_{LO1} = 15$ GHz. To validate this concept, conducting trials with the electrical spectrum emerges as the most efficient confirmation technique.

The proposed cascaded SOA1_SOA-MZI_SOA4 design, based on simultaneous FWM-XPM-XGM mixing, has several practical implications for optical communication and signal processing. The architecture supports wavelength conversion, concurrent handling of multiple signals, and flexible manipulation of signal characteristics through the SOA-MZI, while the combined FWM-XPM-XGM interactions improve signal quality relative to a single-effect mixing stage. These properties make the design applicable to electro-optical signal processing, high-speed data transmission, optical regeneration, and compact photonic integrated circuits (PICs) for signal routing and switching, and the system's adaptability allows it to be reconfigured for a range of RoF and MMW applications. More broadly, cascaded FWM-XPM-XGM mixing of this kind is relevant to ultrafast photonic switching architectures, and the underlying SOA-MZI platform has also been explored

for applications such as quantum key distribution (QKD), suggesting directions for future extensions of this work [67–73].

2.2. Electrical Spectra for the Concurrent Third-Order Up- and Down-Mixed Replicas

In our experiments, we present the electrical spectrum of the FWM signal that contains third-order upward and downward components concurrently at the first stage of the SOA1_SOA-MZI_SOA4 design (SOA1 output), as depicted in Figure 2. This spectrum serves as evidence of the underlying principle in the electro-optical design, enabling simultaneous up- and down-conversion through the FWM nonlinearity within the SOA1. Importantly, the original input RF signal undergoes up-conversion at the frequency component of $2f_{RF} - f_{LO1} = 7$ GHz and down-conversion at $2f_{LO1} - f_{RF} = 5$ GHz. The third-order up- and down-mixed powers are, respectively, -39.5 and -42.5 dBm.

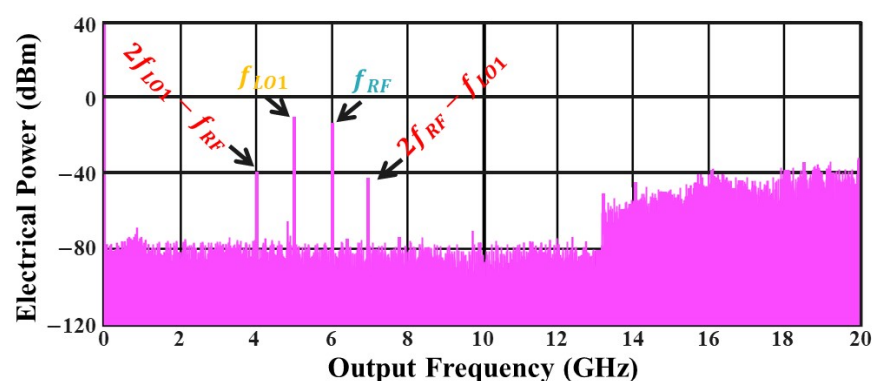


Figure 2. Electrical spectrum of the concurrent third-order up- and down-converted replicas at mixing frequencies $2f_{LO1} - f_{RF}$ and $2f_{RF} - f_{LO1}$, respectively, at the SOA1 output using the FWM interaction for the first stage of the electro-optical SOA1_SOA-MZI_SOA4 design. The frequency of the RF signal is $f_{RF} = 6$ GHz, and the first LO frequency is $f_{LO1} = 5$ GHz.

The electrical spectrum of the sampled signal resulting from the third-order FWM signal, modulated at two frequency components, is illustrated in Figure 3. Examination of the spectrum reveals a frequency up-conversion of the input third-order FWM signal at $2f_{RF} - f_{LO1} = 7$ GHz and $2f_{LO1} - f_{RF} = 4$ GHz. This up-conversion occurs at frequencies $f_{LO2} + 2f_{RF} - f_{LO1}$ and $f_{LO2} + 2f_{LO1} - f_{RF}$, accompanied by down-conversion at $f_{LO2} - 2f_{RF} + f_{LO1}$ and $f_{LO2} - 2f_{LO1} + f_{RF}$. Additionally, the original RF signal at f_{RF} and LO1 signal at f_{LO1} , both concurrently present at the SOA-MZI input, also undergo frequency up-conversion at frequencies $f_{LO2} + f_{RF}$ and $f_{LO2} + f_{LO1}$, along with down-conversion at $f_{LO2} - f_{RF}$ and $f_{LO2} - f_{LO1}$, respectively.

Figure 3, following the band-pass sampling concept, demonstrates the frequency down-conversion of the input third-order FWM signal and both original RF and LO1 signals at four distinct output frequencies as outlined in Table 2. Notably, these output frequencies align with those generated through the basic sampling process. Specifically, for the down-conversion process, two replica powers are achieved at identical frequencies: $|2f_{LO1} - f_{RF} - f_{LO2}| = f_{LO2} - 2f_{LO1} + f_{RF} = 4$ GHz, $|2f_{RF} - f_{LO1} - f_{LO2}| = f_{LO2} - 2f_{RF} + f_{LO1} = 1$ GHz, $|f_{LO1} - f_{LO2}| = f_{LO2} - f_{LO1} = 3$ GHz, and $|f_{RF} - f_{LO2}| = f_{LO2} - f_{RF} = 2$ GHz. It is noteworthy that the frequency of the amplified third-order FWM replica at $2f_{LO1} - f_{RF} = 4$ GHz at the SOA-MZI output matches the frequency related to up- and down-mixed replicas, which are converted from the third-order FWM signal, at $|2f_{LO1} - f_{RF} - f_{LO2}| = f_{LO2} - 2f_{LO1} + f_{RF} = 4$ GHz.

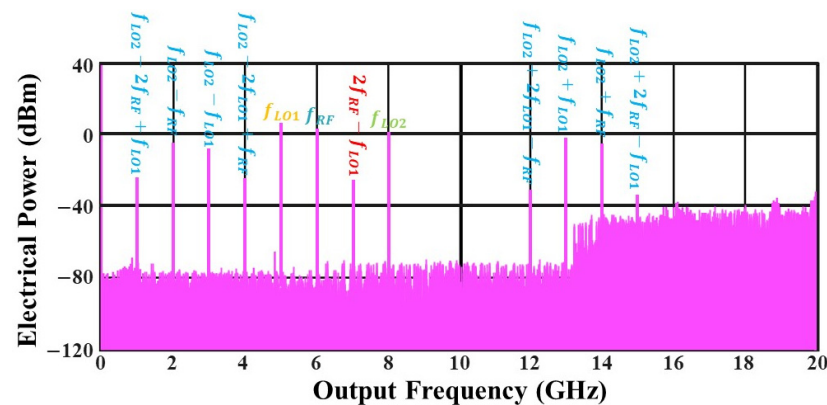


Figure 3. Electrical spectrum of the concurrent third-order up- and down-converted replicas at the SOA-MZI output for the second stage of the electro-optical SOA1_SOA-MZI_SOA4 design using XPM-XGM interactions. The second LO frequency is $f_{LO2} = 8$ GHz.

Consequently, the maximum frequency range of the FWM-XPM-XGM concept extends to 15 GHz, although the frequency span of the incoming FWM signal shown in Figure 2 reaches only 7 GHz. SOA4 provides approximately 20 dB of amplification in electrical power for the concurrent third-order up- and down-converted replicas across the full range of output frequencies, as illustrated in Figure 4; the noise power is also slightly increased.

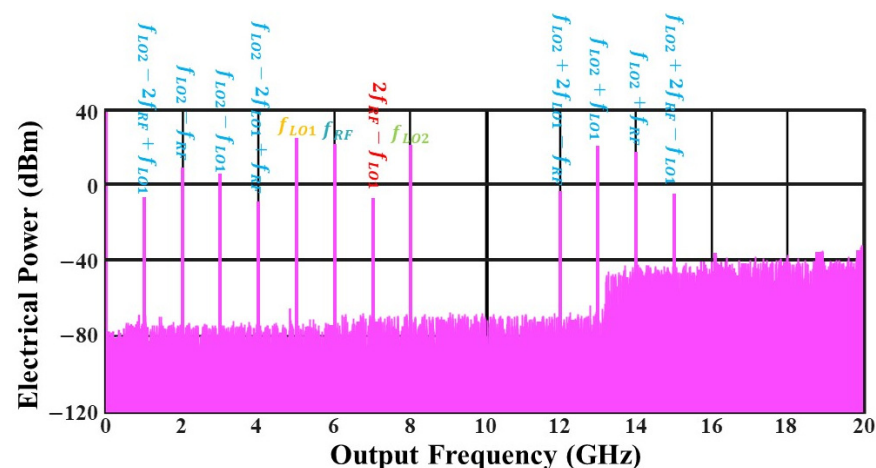


Figure 4. Electrical spectrum of the amplified concurrent third-order up- and down-converted replicas at the SOA4 output for the third stage of the electro-optical SOA1_SOA-MZI_SOA4 design.

2.3. Third-Order Replica Validation

In our experimental setup, we observe that the generation of third-order replicas at the SOA1 output is limited to higher input power levels within a specific wavelength range, a behavior attributed to the FWM interaction. Because FWM is a third-order nonlinear process, its efficiency increases with input power, as shown in Figure 5. At low power levels, the FWM-driven nonlinearity is not strong enough to produce measurable third-order replicas, and other nonlinear effects, such as XGM, dominate instead. This power dependence likely reflects both the intrinsic wavelength dependence of FWM efficiency and the specific material characteristics of SOA1; operating near, but below, the SOA's saturation power may further enhance the nonlinear interactions responsible for the observed replicas. Characterizing these properties of the setup, the optical components, and the conditions that favor FWM is therefore important for understanding this behavior and for optimizing the third-order up- and down-mixed replicas generated through the SOA-MZI.

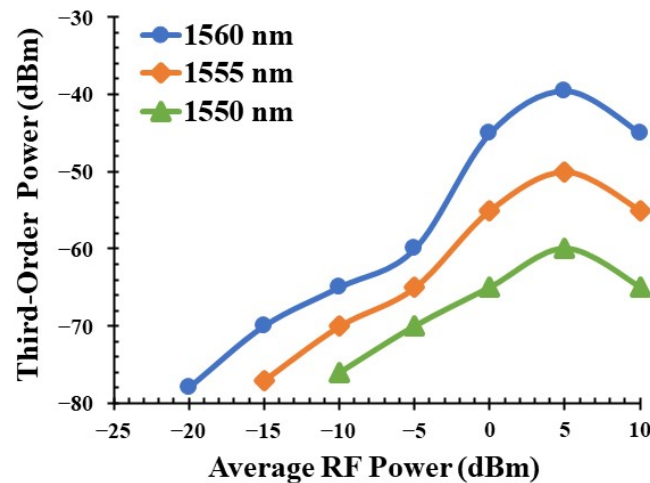


Figure 5. The third-order replica at $2f_{LO1} - f_{RF} = 4$ GHz at the SOA1 output for different wavelengths as well as different average RF powers.

The FWM efficiency depends on the carrier-density modulation depth, but once the total optical power approaches the SOA's saturation power, gain compression clamps that modulation depth, so the nonlinear (third-order) mixing efficiency stops increasing and falls even though input power keeps rising.

The pronounced dependence of third-order power on the nominal RF wavelength reflects the wavelength-dependent gain/loss characteristics of the components generating the electrical RF drive, rather than optical detuning within SOA1 itself, because the RF tone is injected electrically. Small wavelength-dependent variations in the effective electrical drive power delivered to SOA1 are amplified into the observed spread in output power due to the steep dependence of mixing efficiency on RF drive amplitude.

Figure 5 shows that the third-order replica at 4 GHz is generated more efficiently when the RF signal has a wavelength of 1560 nm and an average optical power of 5 dBm, consistent with the electrical spectrum in Figure 2. At this same power level, the third-order replica power drops from -39.5 dBm at 1560 nm to -60 dBm at 1550 nm. Figure 6 shows the electrical spectrum of the concurrent third-order up- and down-converted replicas at 4 GHz and 7 GHz, respectively, generated at the SOA1 output via FWM (the first stage of the SOA1_SOA-MZI_SOA4 design), measured at an RF wavelength of 1550 nm and the same RF power of 5 dBm. This spectrum shows a 20 dB reduction in third-order replica power relative to Figure 2, confirming that 1560 nm yields the higher replica power for this design.

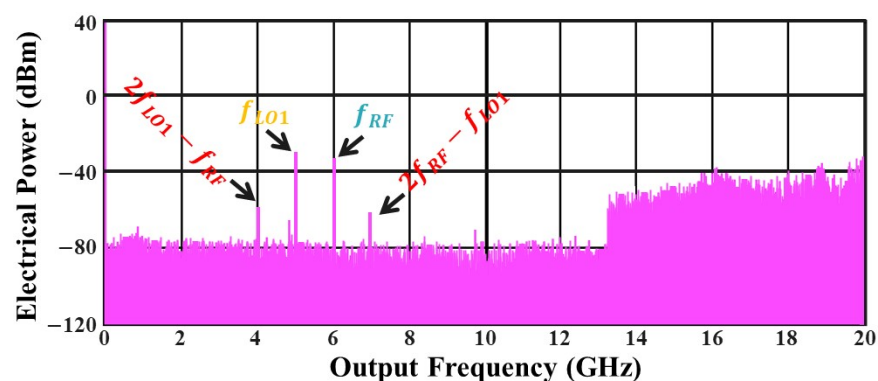


Figure 6. Electrical spectrum of the concurrent third-order up- and down-converted replicas. The wavelength of the RF signal is $\lambda_{RF} = 1550$ nm, and the first LO wavelength is $\lambda_{LO1} = 1565$ nm.

2.4. Conversion Efficiency of the Third-Order Up- and Down-Mixed Replicas

The conversion efficiency (CE) is determined by comparing the electrical power of the RF signal at the input of SOA1 with that of the third-order up- and down-mixed replicas at each stage's output. The initial electrical power of the RF signal is -20 dBm. The CE is exclusively assessed for replicas associated with third-order conversion, although it is feasible to evaluate the CE for other replicas detailed in Figure 3. Notably, the CE exhibits lower values at the SOA1 output (first stage), as illustrated in Table 3, where third-order replicas arise through FWM interaction. These replicas undergo amplification and conversion to higher and lower frequencies at the SOA-MZI output (second stage), which results in elevated CE values. A significant amplification of CE, approximately 14.5 dB for down-mixed replicas at $f_{LO2} - 2f_{RF} + f_{LO1} = 1$ GHz and 10.5 dB for up-conversion replicas at $f_{LO2} + 2f_{RF} - f_{LO1} = 15$ GHz, occurs. This phenomenon can be elucidated by considering that the replicas generated for both up- and down-conversions result from the interplay of carrier density modulation and electrical replica power, as displayed in Figure 7. These replica terms induce carrier density modulation at distinct frequencies for up- and down-conversions. In our specific scenario, the frequency response, characterized by a low-pass behavior [62], leads to higher carrier density modulation at lower frequencies, as illustrated in Figure 7a. Consequently, we can ascertain that the CE is elevated for the down-mixed replica difference at these lower frequencies.

Table 3. Conversion efficiency (CE) of the third-order up- and down-mixed replicas at the output of each stage.

	Third-Order Up-Mixed Replicas		Third-Order Down-Mixed Replicas	
	Output Frequency (GHz)	CE (dB)	Output Frequency (GHz)	CE (dB)
First Stage: SOA1 Output	7	-22.5	4	-19.5
Second Stage: SOA-MZI Output	15	-9	4	-8
	12	-12	1	-5
Third Stage: SOA4 Output	15	14	4	10
	12	16	1	14

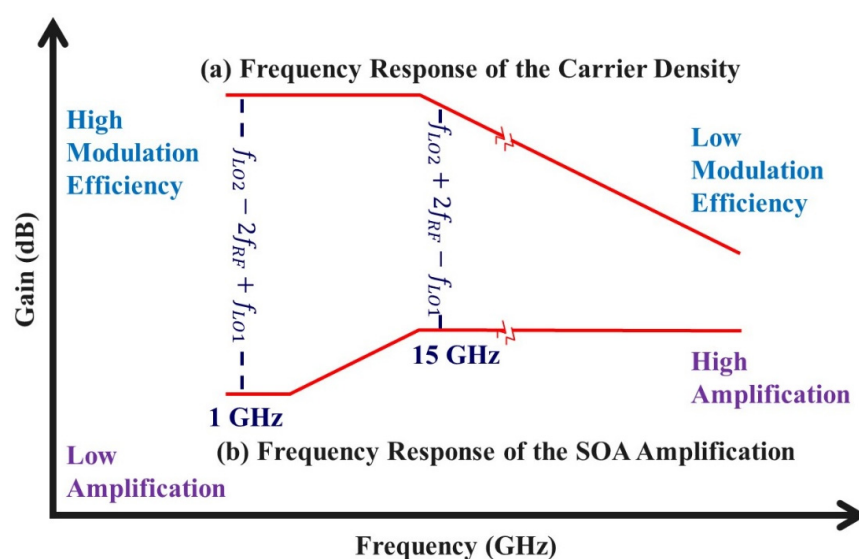


Figure 7. Conceptual diagram of the frequency response of the carrier density (a) and SOA frequency response (b). Curves are qualitative and not to scale; frequency markers correspond to the replica frequencies discussed in the text.

At the third stage's output (SOA4 output), where amplification alone is achieved, the CE reaches 14 dB for down-mixed replicas, compared to the −5 dB at the SOA-MZI output at $f_{LO2} - 2f_{RF} + f_{LO1} = 1$ GHz. Similarly, for up-conversion, the CE reaches 14 dB, contrasting with the −9 dB at the SOA-MZI output at $f_{LO2} + 2f_{RF} - f_{LO1} = 15$ GHz. Due to the frequency response of the SOA [62], there is an additional 11 dB of amplification for up-conversion, as shown in Figure 7. Throughout the frequency response of the employed SOAs, as illustrated in Figure 7b, the amplification of signal replicas sampled at high frequencies exceeds that at low frequencies. On the other hand, the signal has a lower modulation efficiency based on the frequency response of the SOA carrier density as shown in Figure 7a.

3. Conclusions

The cascaded SOA1_SOA-MZI_SOA4 design experimentally demonstrates a third-order electro-optical mixing scheme based on combined FWM-XPM-XGM interactions, enabling the concurrent generation of third-order up- and down-mixed replicas over a frequency range extending up to 15 GHz. Generating and validating these replicas requires careful control of the input signal parameters, including sufficiently high input power within a specific wavelength range; this was verified through electrical spectrum analysis at the output of each stage of the SOA1_SOA-MZI_SOA4 architecture. The design achieves a conversion efficiency of up to 14 dB at 15 GHz at the SOA4 output, which indicates that this SOA-MZI-based concurrent mixing approach is applicable to optical communication and signal processing systems.

The present work establishes the experimental feasibility of concurrent third-order up- and down-mixing in a cascaded SOA1_SOA-MZI_SOA4 architecture. Building on our prior theoretical treatment of XPM- and XGM-based mixing in a standalone SOA-MZI [62], future work will develop a complete theoretical model of the full three-stage SOA1_SOA-MZI_SOA4 design, incorporating FWM in SOA1, combined XPM-XGM in the SOA-MZI, and gain saturation in SOA4, to quantitatively predict the conversion efficiency and frequency response.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

ASE	amplified spontaneous emission
BV	bias voltage
CDM	carrier density modulation
CE	conversion efficiency
CH	carrier heating
EAM	electro-absorption modulator
EOM	electro-optic modulator
ESA	electrical spectrum analyzer
FWM	four-wave mixing
IF	intermediate frequency
LNA	low-noise amplifier
LO	local oscillator

MMW	millimeter wave
MZI	Mach–Zehnder interferometer
MZM	Mach–Zehnder modulator
OBPF	optical band-pass filter
PD	photodiode
PIC	photonic integrated circuit
QKD	quantum key distribution
RF	radio frequency
RoF	radio-over-fiber
SHB	spectral hole burning
SOA	semiconductor optical amplifier
SOA-MZI	semiconductor optical amplifier Mach–Zehnder interferometer
UTC-PD	uni-traveling carrier photodiode
VOA	variable optical attenuator
WiFi	wireless fidelity
XGM	cross-gain modulation
XPM	cross-phase modulation

References

1. Kleine-Ostmann, T.; Nagatsuma, T. A review on terahertz communications research. *J. Infrared Millim. Terahertz Waves* **2011**, *32*, 143–171. [\[CrossRef\]](#)
2. Stöhr, A.; Babel, S.; Cannard, P.J.; Charbonnier, B.; van Dijk, F.; Fedderwitz, S.; Moodie, D.; Pavlovic, L.; Ponnampalam, L.; Renaud, C.C.; et al. Millimeter-wave photonic components for broadband wireless systems. *IEEE Trans. Microw. Theory Tech.* **2010**, *58*, 3071–3082. [\[CrossRef\]](#)
3. Smith, G.H.; Novak, D.; Lim, C. A millimeter-wave full-duplex fiber-radio star-tree architecture incorporating WDM and SCM. *IEEE Photonics Technol. Lett.* **1998**, *10*, 1650–1652. [\[CrossRef\]](#)
4. Rouvalis, E.; Renaud, C.; Moodie, D.G.; Robertson, M.J.; Seeds, A.J. Traveling-wave Uni-Traveling Carrier Photodiodes for continuous wave THz generation. *Opt. Express* **2010**, *18*, 11105–11110. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Ito, H.; Kodama, S.; Muramoto, Y.; Furuta, T.; Nagatsuma, T.; Ishibashi, T. High-speed and high-output InP-InGaAs unitraveling-carrier photodiodes. *IEEE J. Sel. Top. Quantum Electron.* **2004**, *10*, 709–727. [\[CrossRef\]](#)
6. Preu, S.; Döhler, G.H.; Malzer, S.; Wang, L.J.; Gossard, A.C. Tunable, continuous-wave terahertz photomixer sources and applications. *J. Appl. Phys.* **2011**, *109*, 061301. [\[CrossRef\]](#)
7. Thomas, V.A.; El-Hajjar, M.; Hanzo, L. Millimeter-wave radio over fiber optical upconversion techniques relying on link nonlinearity. *IEEE Commun. Surv. Tutor.* **2016**, *18*, 29–53. [\[CrossRef\]](#)
8. Sun, C.K.; Orazi, R.J.; Pappert, S.A.; Burns, W.K. A photonic-link millimeter-wave mixer using cascaded optical modulators and harmonic carrier generation. *IEEE Photonics Technol. Lett.* **1996**, *8*, 1166–1168. [\[CrossRef\]](#)
9. Park, C.S.; Oh, C.K.; Lee, C.G.; Kim, D.-H.; Park, C.-S. A photonic up-converter for a WDM radio-over-fiber system using cross-absorption modulation in an EAM. *IEEE Photonics Technol. Lett.* **2005**, *17*, 1950–1952. [\[CrossRef\]](#)
10. Termos, H.; Mansour, A. Quadrature amplitude modulation frequency up- and down-conversions using a positive-intrinsic-negative photodiode sampling mixer. *Opt. Eng.* **2022**, *61*, 096103. [\[CrossRef\]](#)
11. Paresys, F.; Shao, T.; Maury, G.; Le Guennec, Y.; Cabon, B. Bidirectional millimeter-wave radio-over-fiber system based on photodiode mixing and optical heterodyning. *J. Opt. Commun. Netw.* **2013**, *5*, 74–80. [\[CrossRef\]](#)
12. Seo, Y.-K.; Choi, C.-S.; Choi, W.-Y. All-optical signal up-conversion for radio-on-fiber applications using cross-gain modulation in semiconductor optical amplifiers. *IEEE Photonics Technol. Lett.* **2002**, *14*, 1448–1450. [\[CrossRef\]](#)
13. Kim, H.; Song, H.; Song, J. All-optical frequency up-conversion technique using four-wave mixing in semiconductor optical amplifiers for radio-over-fiber applications. In Proceedings of the IEEE/MTT-S International Microwave Symposium, Honolulu, HI, USA, 3–8 June 2007; pp. 67–70.
14. Kim, H.-J.; Song, J.-I. Simultaneous WDM RoF signal generation utilizing an all-optical frequency up converter based on FWM in an SOA. *IEEE Photonics Technol. Lett.* **2011**, *23*, 828–830. [\[CrossRef\]](#)
15. Termos, H.; Mansour, A. Concurrent M-QAM transmission performance assessment in a combined four SOA-MZIs arrangement. *Opt. Lasers Eng.* **2024**, *176*, 108110. [\[CrossRef\]](#)
16. Song, H.-J.; Lee, J.S.; Song, J.-I. Signal up-conversion by using a cross-phase-modulation in all-optical SOA-MZI wavelength converter. *IEEE Photonics Technol. Lett.* **2004**, *16*, 593–595. [\[CrossRef\]](#)

17. Song, H.J.; Lee, J.S.; Song, J.I. All-Optical Harmonic Frequency Up-Conversion for a WDM Radio over Fiber System. *IEEE Conf. Microw. Symp. Dig.* **2004**, *1*, 405–407. [\[CrossRef\]](#)
18. Mishina, K.; Nissanka, S.M.; Maruta, A.; Mitani, S.; Ishida, K.; Shimizu, K.; Hatta, T.; Kitayama, K. All-optical modulation format conversion from NRZ-OOK to RZ-QPSK using parallel SOA-MZI OOK/BPSK converters. *Opt. Express* **2007**, *15*, 7774–7785. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Turkiewicz, J.P. All-optical OOK-to-QAM modulation format conversion utilizing parallel SOA-MZI wavelength converters. *Microw. Opt. Technol. Lett.* **2011**, *54*, 2429–2433. [\[CrossRef\]](#)
20. Mishina, K.; Kono, T.; Maruta, A.; Kitayama, K. All-optical OOK-to-16QAM format conversion by using SOA-MZI wavelength converters. In Proceedings of the 17th Opto-Electronics and Communications Conference, Busan, Korea, 2–6 July 2012.
21. Mishina, K.; Hisano, D.; Maruta, A. All-Optical Modulation Format Conversion and Applications in Future Photonic Networks. *IEICE Trans. Electron.* **2019**, *102*, 304–315. [\[CrossRef\]](#)
22. Leuthold, J.; Besse, P.; Eckner, J.; Gamper, E.; Dulk, M.; Melchior, H. All-optical space switches with gain and principally ideal extinction ratios. *IEEE J. Quantum Electron.* **1998**, *34*, 622–633. [\[CrossRef\]](#)
23. Termos, H.; Mansour, A.; Ebrahim-Zadeh, M. Establishment of an electro-optical mixing design on a photonic SOA-MZI using a differential modulation arrangement. *Sensors* **2023**, *23*, 4380. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Termos, H.; Mansour, A. All-Optical Three-Input “AND” Gate Dependent on a Differential Modulation Architecture. *Electronics* **2023**, *12*, 1510. [\[CrossRef\]](#)
25. Termos, H.; Mansour, A. High-repetition-rate femtosecond “OR” gate design in a differential SOA-MZI. *Optik* **2024**, *304*, 171760. [\[CrossRef\]](#)
26. Kim, J.H.; Kim, B.C.; Byun, Y.T.; Jeon, Y.M.; Lee, S.; Woo, D.H. All-optical AND gate using cross-gain modulation in semiconductor optical amplifiers. *Jpn. J. Appl. Phys.* **2004**, *43*, 608–610. [\[CrossRef\]](#)
27. Kang, B.-K.; Kim, J.H.; Byun, Y.T.; Lee, S.; Jhon, Y.M.; Woo, D.H.; Yang, J.S.; Kim, S.H.; Park, Y.H.; Yu, B.G. All-optical AND gate using probe and pump signals as the multiple binary points in cross phase modulation. *Jpn. J. Appl. Phys.* **2002**, *41*, L568–L570. [\[CrossRef\]](#)
28. Dimitriadou, E.; Zoiros, K.E. On the design of reconfigurable ultrafast all-optical NOR and NAND gates using a single quantum dot semiconductor optical amplifier-based Mach-Zehnder interferometer. *J. Opt.* **2012**, *14*, 105401. [\[CrossRef\]](#)
29. Termos, H.; Kallas, K. Performance Characterizations of a Simultaneous “AND”-“OR” Gates System Dependent on a Parallel-Series SOA-MZIs Combination. *J. Electron. Electr. Eng.* **2026**, *5*, 181. [\[CrossRef\]](#)
30. Kim, J.-Y.; Kang, J.-M.; Kim, T.-Y.; Han, S.-K. All-Optical Multiple Logic Gates With XOR, NOR, OR, and NAND Functions Using Parallel SOA-MZI Structures: Theory and Experiment. *J. Light. Technol.* **2006**, *24*, 3392. [\[CrossRef\]](#)
31. Dong, J.; Zhang, X.; Xu, J.; Huang, D. 40 Gb/s all-optical logic NOR and OR gates using a semiconductor optical amplifier: Experimental demonstration and theoretical analysis. *Opt. Commun.* **2008**, *281*, 1710–1715. [\[CrossRef\]](#)
32. Li, Z.; Li, G. Ultrahigh-speed reconfigurable logic gates based on four-wave mixing in a semiconductor optical amplifier. *IEEE Photonics Technol. Lett.* **2006**, *18*, 1341–1343. [\[CrossRef\]](#)
33. Sun, H.; Wang, Q.; Dong, H.; Dutta, N.K. XOR performance of a quantum dot semiconductor optical amplifier-based Mach-Zehnder interferometer. *Opt. Express* **2005**, *13*, 1892–1899. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Stubkjaer, K.E. Semiconductor optical amplifier-based all optical gates for high-speed optical processing. *IEEE J. Sel. Top. Quantum Electron.* **2000**, *6*, 1428–1435. [\[CrossRef\]](#)
35. Soto, H.; Topomondzo, J.D.; Erasme, D.; Castro, M. All-optical NOR gates with two and three input logic signals based on cross-polarization modulation in a semiconductor optical amplifier. *Opt. Commun.* **2003**, *218*, 243–247. [\[CrossRef\]](#)
36. Bintjas, C.; Kalyvas, M.; Theophilopoulos, G.; Stathopoulos, T.; Avramopoulos, H.; Occhi, L.; Schares, L.; Guekos, G.; Hansmann, S.; Dall’Ara, R. 20 Gb/s All-optical XOR operation with UNI Gate. *IEEE Photonics Technol. Lett.* **2000**, *12*, 824–836. [\[CrossRef\]](#)
37. Awad, E.S.; Cho, P.; Goldhar, J. High-Speed All-Optical AND Gate Using Nonlinear Transmission of Electro absorption Modulator. *IEEE Photonics Technol. Lett.* **2001**, *13*, 472–474. [\[CrossRef\]](#)
38. Yeh, C.H.; Sung, J.Y.; Yang, L.G.; Chow, C.W.; Chen, J.H. Stable and wavelength-tunable RSOA-and SOA-based fiber ring laser. *Opt. Fiber Technol.* **2014**, *20*, 250–253. [\[CrossRef\]](#)
39. Termos, H. Comparative Analysis of Linear, X, V, and Ring Fiber Cavity Lasers with SOA-MZI Integration for Ultra-High-Speed Data Transmission. *Opt. Fiber Technol.* **2026**, *99*, 104623. [\[CrossRef\]](#)
40. Termos, H.; Mansour, A. Experimental topology of a femtosecond ring fiber cavity laser using SOA-MZI for coincident OFDM dispatch. *Opt. Laser Technol.* **2025**, *182*, 112076. [\[CrossRef\]](#)
41. Peng, P.C.; Feng, K.M.; Peng, W.R.; Chiou, H.Y.; Chang, C.C.; Chi, S. Long-distance fiber grating sensor system using a fiber ring laser with EDWA and SOA. *Opt. Commun.* **2005**, *252*, 127–131. [\[CrossRef\]](#)
42. Lee, Y.W.; Jung, J.; Lee, B. Multiwavelength-switchable SOA-fiber ring laser based on polarization-maintaining fiber loop mirror and polarization beam splitter. *IEEE Photonics Technol. Lett.* **2004**, *16*, 54–56. [\[CrossRef\]](#)

43. El Hassanieh, R.; Morel, P.; Hamze, M.; Quintard, V.; Perennou, A.; Sharaiha, A. Experimental OFDM transmission performance analysis in a SOA—Fiber cavity laser. *Opt. Express* **2023**, *31*, 24875–24886. [[CrossRef](#)] [[PubMed](#)]
44. Hu, Z.; Li, F.; Pan, Z.; Tan, W. Wavelength-tunable narrow-linewidth semiconductor fiber-ring laser. *IEEE Photonics Technol. Lett.* **2000**, *12*, 977–979. [[CrossRef](#)]
45. Deng, M.L.; Cao, B.Y.; Giddings, R.P.; Dong, Y.X.; Jiang, N.; Nesses, D.; Qiu, K.; Tang, J.M. Intra-Cavity Chromatic Dispersion Impacts on 10-Gb/s Optical OFDM Transmissions Over 25-km Dual-RSOA-Based Self-Seeded PON Systems. *IEEE Photonics J.* **2015**, *7*, 7200112. [[CrossRef](#)]
46. Komljenovic, T.; Babić, D.; Sipus, Z. 47-km 1.25-Gbps transmission using a self-seeded transmitter with a modulation averaging reflector. *Opt. Express* **2012**, *20*, 17386–17392. [[CrossRef](#)] [[PubMed](#)]
47. Šprem, M.; Babić, D. Wavelength reuse WDM-PON using RSOA and modulation averaging. *Opt. Commun.* **2019**, *451*, 1–5. [[CrossRef](#)]
48. Yeh, C.H.; Chen, H.Z.; Chen, J.Y.; Chow, C.W. *Utilizing New Erbium-Doped Fiber Laser Scheme for Long-Distance Fiber Bragg Grating (FBG) Sensor System*; IEEE: New York, NY, USA, 2015; pp. 1–3. [[CrossRef](#)]
49. Yeh, C.-H.; Chi, S. Fibre-fault monitoring technique for passive optical networks based on fibre Bragg gratings and semiconductor optical amplifier. *Opt. Commun.* **2006**, *257*, 306–310. [[CrossRef](#)]
50. Meltz, G.; Morey, W.W.; Glenn, W.H. Formation of Bragg gratings in optical fibre by a transverse holographic method. *Opt. Lett.* **1989**, *14*, 823–825. [[CrossRef](#)] [[PubMed](#)]
51. Melle, S.M.; Liu, K.; Measures, R.M. A passive wavelength demodulation system for guided-wave Bragg grating sensors. *IEEE Photonics Technol. Lett.* **1992**, *4*, 516–518. [[CrossRef](#)]
52. Xu, Y.Z.; Tam, H.Y.; Du, W.C.; Demokan, M.S. Tunable dualwavelength-switching fiber grating laser. *IEEE Photonics Technol. Lett.* **1998**, *10*, 334–336. [[CrossRef](#)]
53. Zhao, D.; Li, S.; Chan, K.T. Precise and rapid wavelength-switching of fiber laser using semiconductor optical amplifier. *Electron. Lett.* **2001**, *37*, 945–946.
54. Lee, M.; Yu, J.; Kim, Y.; Kang, C.-H.; Park, J. Design of hierarchical cross connect WDM networks employing a two-stage multiplexing scheme of waveband and wavelength. *IEEE J. Sel. Areas Commun.* **2002**, *20*, 166–171. [[CrossRef](#)]
55. Yu, B.-A.; Kwon, J.; Chung, S.; Seo, S.-W.; Lee, B. Multiwavelength switchable SOA-fiber ring laser using a sampled Hi-Bi fiber grating. *Electron. Lett.* **2003**, *39*, 649–650. [[CrossRef](#)]
56. Jolley, N.E.; Kee, H.; Pickard, P.; Tang, J.; Cordina, K. Generation and propagation of a 1550 nm 10 Gbit/s optical orthogonal frequency division multiplexed signal over 1000 m of multimode fibre using a directly modulated DFB. In Proceedings of the OFC/NFOEC Technical Digest. Optical Fiber Communication Conference, Anaheim, CA, USA, 6–11 March 2005; Volume 6, p. 3.
57. D'Ottavi, A.; Iannone, E.; Mecozzi, A.; Scotti, S.; Spano, P.; Dall'Ara, R.; Eckner, J.; Guekos, G. Efficiency and noise performance of wavelength converters based on FWM in semiconductor optical amplifiers. *IEEE Photonics Technol. Lett.* **1995**, *7*, 357–359. [[CrossRef](#)]
58. Connelly, M.J. *Semiconductor Optical Amplifiers*; Kluwer Academic Publishers: Boston, MA, USA, 2002.
59. Termos, H.; Mansour, A.; Nasser, A. Simultaneous up and down frequency mixing based on a cascaded SOA-MZIs link. *Appl. Opt.* **2021**, *60*, 8336–8348. [[CrossRef](#)] [[PubMed](#)]
60. Gomes, N.J.; Monteiro, P.P.; Gameiro, A. *Next Generation Wireless Communications Using Radio Over Fiber*; Wiley: Hoboken, NJ, USA, 2012.
61. CIP Photonics. *Preliminary Datasheet 40G-2R2-ORP: Twin 40 Gb/s 2R Optical Regenerator*; CIP Photonics: Suffolk, UK, 2014.
62. Termos, H. Study of Up and Down Conversion Technique by All Optical Sampling Based on a SOA-MZI. Ph.D. Thesis, Université de Bretagne Occidentale, Brest, France, 2017.
63. Rouvalis, E.; Fice, M.J.; Renaud, C.C.; Seeds, A.J. Millimeter-wave optoelectronic mixers based on uni-traveling carrier photodiodes. *IEEE Trans. Microw. Theory Tech.* **2012**, *60*, 686–691. [[CrossRef](#)]
64. Giboney, K.S.; Rodwell, M.J.W.; Bowers, J.E. Traveling-wave photodetector theory. *IEEE Trans. Microw. Theory Tech.* **1997**, *45*, 1310–1319. [[CrossRef](#)]
65. Spyropoulou, M.; Pleros, N.; Miliou, A. SOA-MZI-based nonlinear optical signal processing: A frequency domain transfer function for wavelength conversion, clock recovery, and packet envelope detection. *IEEE J. Quantum Electron.* **2011**, *47*, 40–49. [[CrossRef](#)]
66. Vaughan, R.G.; Scott, N.L.; White, D.R. The theory of bandpass sampling. *IEEE Trans. Signal Process.* **1991**, *39*, 1973–1984. [[CrossRef](#)]
67. Yu, H.; Sciara, S.; Chemnitz, M.; Montaut, N.; Crockett, B.; Fischer, B.; Helsten, R.; Wetzel, B.; Goebel, T.A.; Krämer, R.G.; et al. Quantum key distribution implemented with d-level time-bin entangled photons. *Nat. Commun.* **2025**, *16*, 171. [[CrossRef](#)] [[PubMed](#)]
68. Termos, H. Quantum authentication evolution: Novel approaches for securing quantum key distribution. *Entropy* **2024**, *26*, 447. [[CrossRef](#)] [[PubMed](#)]

69. Wang, L.-J.; Zhang, K.-Y.; Wang, J.-Y.; Cheng, J.; Yang, Y.-H.; Tang, S.-B.; Yan, D.; Tang, Y.-L.; Liu, Z.; Yu, Y.; et al. Experimental authentication of quantum key distribution with post-quantum cryptography. *npj Quantum Inf.* **2021**, *7*, 67. [[CrossRef](#)]
70. Fung, C.-H.F.; Ma, X.; Chau, H.F. Practical issues in quantum-key-distribution post-processing. *Phys. Rev. A* **2010**, *81*, 012318. [[CrossRef](#)]
71. Branciard, C.; Gisin, N.; Kraus, B.; Scarani, V. Security of two quantum cryptography protocols using the same four qubit states. *Phys. Rev. A Gen. Phys.* **2005**, *72*, 032301. [[CrossRef](#)]
72. Ekert, A.; Christandl, M.; Renner, R. A generic security proof for quantum key distribution. *Harvard. Edu. arXiv* **2004**. [[CrossRef](#)]
73. Feng, Z.; Li, S.; Xu, Z. Experimental underwater quantum key distribution. *Opt. Express* **2021**, *29*, 8725–8736. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.