Optimization of system's parameters for wavelength conversion of E-band signals

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ABSTRACT

Current and future wireless communication systems are designed to achieve the user's demands such as high data rate and high speed with low latency and simultaneously to save bandwidth and spectrum. In 5G and 6G networks, a high speed of transmitting and switching is required for internet of things (IoT) applications with higher capacity. To achieve these requirements a semiconductor optical amplifier (SOA) is considered as a wavelength converter to transmit a signal with an orthogonal frequency division multiplexing with subcarrier power modulation (OFDM-SPM). It exploits the subcarrier's power in conventional OFDM block in order to send additional bits beside the normally transmitted bits. In this paper, we optimized the SOA's parameters to have efficient wavelength conversion process. These parameters are included the injection current (IC) of SOA, power of pump and probe signals. A 7 Gbps OFDM-SPM signal with a millimeter waves (MMW) carrier of 80 GHz is considered for signal switching. The simulation results investigated and analyzed the performance of the designed system in terms of error vector magnitude (EVM), bit error rate (BER) and optical signal-to-noise ratio (OSNR). The optimum value of IC is 0.6 A while probe power is 9.45 and 8.9 dBm for pump power. The simulation is executed by virtual photonic integrated (VPI) software.

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1. INTRODUCTION

The huge demands on high capacity and bandwidth (BW) interactive applications such as virtual reality (VR) and autonomous vehicles are considered as the main motivators to find the next generations of wireless technologies. The standardization of the current fifth-generation (5G) is driven by the enhancement of millimeter-wave (MMW) technology [1]. Additionally, in 5G mobile networks, the integration of advanced technologies in access techniques, data modulation, frequency bands, and antenna designs helps to achieve the user's demands [2], [3] However, MMW signals which provide higher bandwidth and data rate (Gbps) suffer from power drop due to the attenuation in a high-frequency band which leads to difficulties of new mobile technology connectivity. This issue can be resolved by integration of photonics and MMW using the concept of millimeter-wave-over-fiber (MMWoF) [4]–[6] as shown in Figure 1 [7]. Moreover, the features of photonic components and devices can be exploited in order to establish different types of electronic systems Photonic devices are playing a key role in switching and routing because it provides main requirements of all wavelength converters (WCs) and optical switches such as low latency, high bandwidth, flexibility, and transparency [7]. One type of wavelength converters can be used based on a semiconductor optical amplifier (SOA) by exploiting its nonlinear effects; self-phase modulation (SPM), cross gain modulation (XGM), and four-wave mixing (FWM) [7].

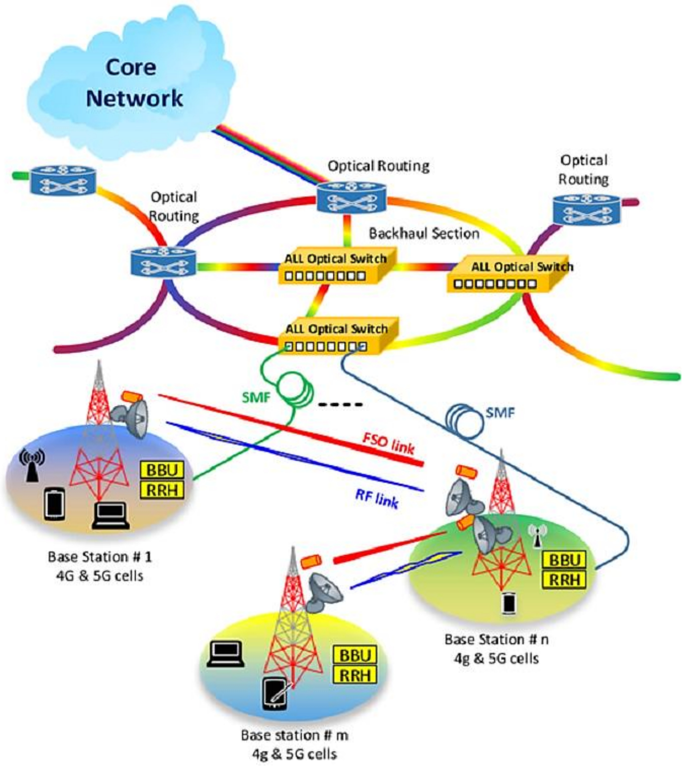


Figure 1. Architecture photonic switching with millimeter-wave over fiber: radio frequency (RF), free-space optical (FSO), remote radio head (RRH), baseband unit (BBU), and single-mode fiber (SMF) [7]

Moreover, the 5G wireless networks have been designed and studied to achieve the demand for higher bandwidth and data rates, so it should find a suitable modulation format that can be used to save bandwidth in current-generation 5G and next-generation 6G and beyond. In previous generations like 4G, orthogonal frequency division multiplexing (OFDM) has been used to achieve higher data rates [8]. On the other hand, it is suffering from a high peak-to-average power ratio (PAPR), so the authors in [9] proposed a new method including modified tone reservation to mitigate PAPR value with low complexity of implementation compared with classical tone reservation (TR) method. Moreover, Abid *et al.* [10] proposed another technique to reduce PAPR which uses discrete cosine transform (DCT), low-density parity-check code (LDPC), and μ-law companding. Additionally, linear amplifiers are used in orthogonal frequency division multiplexing (OFDM) to ensure that the PAPR is accommodated and no distortions are resulted in the output signals [11]. Hajar *et al.* [12] proposed a new modulation scheme which is called orthogonal frequency division multiplexing with subcarrier power modulation (OFDM-SPM). It exploits the subcarrier's power in conventional OFDM block in order to send additional bits beside the normally transmitted bits.

Due to the aforementioned advantages of switching and wavelength conversion using SOA, the authors paid more interest in this regard. Saadaoui *et al.* [13] implemented a photonic system based on MMW switching experimentally for quadrature phase shift keying (QPSK) signal with carrier frequency 30 GHz to carry 3Gbaud data rate. While in [14] demonstrated experimentally a system with a 16-QAM signal to transmit 200 Mbps at the carrier frequency of 20 GHz. In addition, Li *et al.* [15] studied the system of an ultra-high-speed transmission based on all-optical wavelength conversion to transmit the bit rate of 227 Gbps with a modulation format of 128-QAM using SOA. Alkhlefat *et al.* [16] compared between universal filtered multi carrier (UFMC) and filter bank multi-carrier (FBMC) in the wavelength conversion using SOA and proposed the recommended parameters which provide an efficient conversion. In [17], a wavelength conversion of QPSK signal with 9 Gbps data rate and 30 GHz carrier frequency has been investigated using OptiSystem software. The results show that the spacing between pump and probe wavelength is equal to 1.6 nm. Lee and Song [18] implemented experimentally an radio-over-fiber (RoF) downlink by using the up-conversion technique in SOA for a cross-polarization modulation (XPolM) in order to transmit 16-QAM OFDM signal with 10 Gbps and 60 GHz carrier frequency. In [19], MMW signal 16-QAM OFDM with 30 GHz carrier frequency and 10 Gbps data rate was implemented using simulation via VPI software and then the performance was analyzed.

In this paper, a wavelength conversion system and MMW switching using SOA for a signal of OFDM-SPM, which is well-appropriate for 5G and 6G communication networks is proposed. Firstly, a simulation model has been established in the software of VPI transmission Maker to convert the OFDM-SPM signal from one wavelength to another one and to optimize the SOA's parameters to obtain the high system performance in terms of optical signal-to-noise ratio (OSNR), error vector magnitude (EVM), and bit error rate (BER).

The remaining sections of the paper are ordered: in section 2, we discuss and describe the proposed modulation format OFDM-SPM and how it works. Moreover, section 2 shows how the signal is traveling through SOA. Sections 3 and 4 display the simulation model and the simulation results, respectively. Section 5 provides the conclusion of the results.

2. RESEARCH METHOD

In this section, we describe the system model of OFDM-SPM which is considered a suitable modulation technique for next generation networks in terms of transmitter and receiver. Then we describe the theoretical model for SOA and the travelling wave through it.

2.1. OFDM-SPM

In recent researches, there are additional modulation techniques that are exploiting the third dimension together with an existing 2-D signal plan in order to send additional information. The third dimension can be used based on the application, its capabilities, and requirements. Examples of these new emerging modulation techniques are OFDM-SPM, OFDM-index modulation (OFDM-IM), spatial modulation orthogonal frequency division multiplexing (SM-OFDM), OFDM with pulse superposition modulation (OFDM-PSM), and OFDM with subcarrier number modulation (OFDM-SNM) [20].

In this work we will use a modulation scheme that is suitable to be used in next-generation networks; it is called OFDM-SPM. We will use it in MMW switching and wavelength conversion using SOA and optimize the SOA's parameters to obtain higher system performance. In OFDM-SPM, the third dimension has been added in order to carry more data. This dimension is defined as the power of OFDM subcarriers and it can be used to send additional data bits while using OFDM subcarriers for transmitting modulated data symbols. Hajar *et al.* [12] show that the proposed OFDM-SPM provides better performance and high spectral gain than classical OFDM with binary phase-shift keying (BPSK). This is due to half number of subcarriers required in OFDM-SPM comparing with conventional OFDM with BPSK to transmit a bit sequence. Consequently, the OFDM-SPM improving the system as it doubles the spectral efficiency and throughput for high OSNR values. In addition, the transmission power in OFDM-SPM is reduced to half with a saving of spectral gain.

2.1.1. Transmitter part

OFDM-SPM utilizes the subcarrier's power in the symbol of classical OFDM, in order to send two or more bits per subcarrier. Figure 2(a) displays the transmitter of OFDM-SPM while Figure 2(b) displays the receiver part. In Figure 2(a), incoming bits ($2n$) are divided into two sets of n bits, which represent the subcarrier's number in the classical OFDM block utilized to convey data. The function of the first n bit is determining the short circuit (SC) power, where i^{th} bit determines the i^{th} SC power level which is used to carry data. A 1 and 0 are used to set the SC power to high and low respectively. The second n bits are indicating to the bits which need modulation using normal BPSK modulation format. Then the symbols of BPSK are allocated to their corresponding subcarriers [12].

2.1.2. Receiver part

As can be seen in Figure 2(b), the most important advantage of the OFDM-SPM receiver is the simplicity which makes it an attractive technique. At the receiving end, the received data bits pass through the conventional OFDM process. Then the signal is distributed into two demodulation blocks. The first block is working as a bit detector carried by the SC power levels. This is accomplished by making the given threshold value T as a reference and compare it with the received power value of each SC. The threshold T can be defined as the power of the midpoint between high and low-level amplitudes of SCs. If the power of SC is higher than the threshold, it is considered as a high-power SC with naming 1 and vice versa. The second demodulator is responsible for the demodulation of conventional BPSK to the symbols [12].

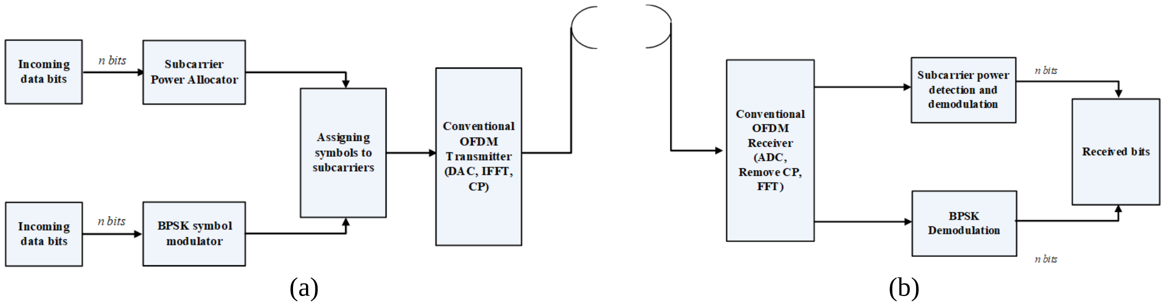


Figure 2. Block diagram of OFDM-SPM: (a) transmitter and (b) receiver

2.2. Semiconductor optical amplifier

Recently, optical amplifiers are playing an essential role in the telecommunication networks such as wavelength division multiplexing (WDM) systems and RoF applications. SOA has some features (e.g., low cost, small size and can be integrated with other components and modulators) that make it important in many applications [21]. Additional advantages of SOA that it has a short time response, high gain, low power, and multifunctional capabilities [22]. The below section is describing the traveling wave through SOA in VPI software [23]. Note that L is the length of the device and the physical amounts are averaged over L [23].

The amplifier's gain medium is depending on the carrier density (N) and described by the material gain coefficient $g(N)$ that is written by [24]:

$$g(N) = \frac{dg}{dN}\,(N - N_{tr}) \tag{1}$$

where $\frac{dg}{dN}$ represents the differential gain, which describing a slope of $g(N)$. and N_{tr} is the value of carrier density at the transparency point.

The optical confinement factor (Γ) is the key factor in SOA which determines the actual amplification of the optical waves in SOA. It can be defined as a fraction of the mode power in the active layer and by the losses of waveguide (α_s). the net gain coefficient $g_{tot}(N)$ is given by [24]:

$$g_{tot}(N) = \Gamma\, g(N) - \alpha_s \tag{2}$$

At each point z of SOA, we can calculate the total gain $G(z)$ of an optical wave as the following [23]:

$$G(N,z) = \exp\,[g_{tot}(N)\ z] = \exp\,[(\Gamma\, g(N) - \alpha_s)\ z] \tag{3}$$

Assuming that the carrier density $N(z)$ is constant over the length of SOA and with using (3), the average light power P_{avg} over the SOA's length can be written as [24]:

$$P_{avg} = \frac{1}{L}\int_0^L P(N,z)\,dz = \frac{1}{L}\int_0^L P_{in} G(N,z)\,dz = \frac{P_{in}}{L}\int_0^L \exp\,[g_{tot}(N)z]\,dz$$
$$= P_{in}\frac{\exp\,[g_{tot}(N)\,L] - 1}{g_{tot}(N)\,L} \tag{4}$$

where P_{avg} is the time function because the carrier density $N(t)$ and the input signal power are time-dependent in (4). Accordingly, the dynamic equation of carrier density $N(t)$ can be expressed as [24]:

$$\frac{dN}{dt} = \frac{I}{qV} - R(N) - \frac{\Gamma\, g(N) P_{avg}(N,t) L}{Vhf} \tag{5}$$

where q is the electron charge, V is the volume which equals to $L * d * W$, d is the thickness and W is the width of the active layer and I is the injection current. h represents Planck's constant and f is the light frequency. The recombination rate $R(N)$ consists of nonradiative transitions and spontaneous emission can be expressed with Auger recombination [25]:

$$R(N) = AN + BN^2 + CN^3 \tag{6}$$

where A, B, and C are constants representing different recombination processes. The (5) and (6) are solved by using the numerical method which is the fifth-order Runge-Kutta algorithm. The output optical field $E_{out}(t)$ is calculated in terms of the input field $E_{in}(t)$ and expressed as [25]:

$$E_{out}(t) = E_{in}(t)\ exp\ \left[\frac{(1+j\alpha)\Gamma\ g(N(t))L - \alpha_s\ L}{2}\right] \tag{7}$$

where α is the linewidth enhancement factor.

3. SIMULATION MODEL

Figure 3 displays the simulation model of the wavelength conversion process using SOA for OFDM-SPM modulated signal. It consists of three stages: transmitter (Tx), wavelength converter (WC), and finally the receiver (Rx). The transmitter includes a laser diode which is considered as the main system carrier operating at wavelength 1550.116 nm (193.4 THz) and a constant laser called pump laser which is working at 1548.515 nm (193.6 THz). The electrical signal OFDM-SPM operating in E-band with carrier frequency 80GHz is generated to transmit a 7 Gbps data rate. Now, laser diode signal and OFDM-SPM signal launched into Mach–Zehnder modulator (MZM) to produced one modulated signal which is called a probe signal. Then both signals; probe and pump are combined in the optical coupler (OC) with a coupling ratio (50:50) in the WC stage then injected into the SOA with an injection current (IC) of 600 mA in order to be transferred to the desired wavelength. Finally, the resulted optical signal will enter the receiver stage, be detected, and then de-modulated using photodetector (PD) in order to measure the performance of conversion in terms of BER, EVM, and OSNR.

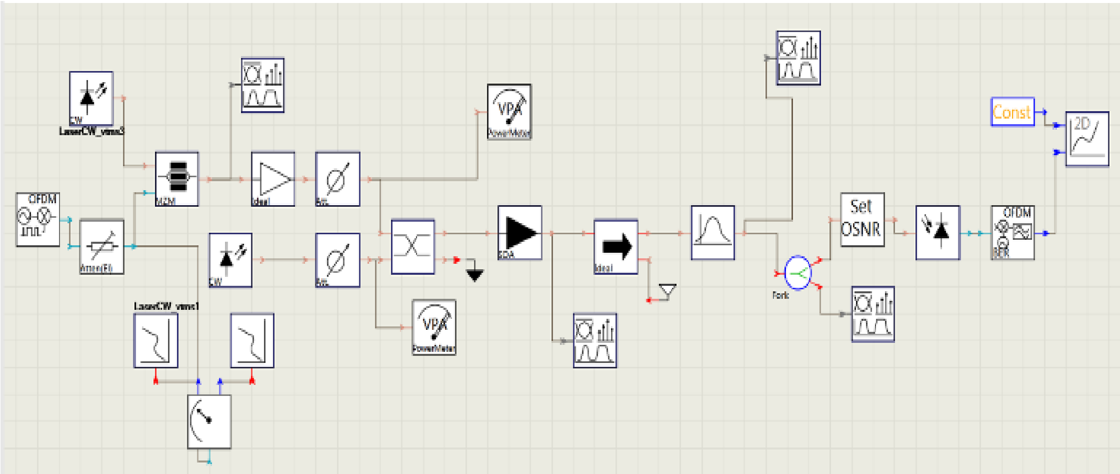


Figure 3. Simulation model for wavelength converter using SOA of OFDM-SPM signal

4. SIMULATION RESULTS

In this section, we will discuss the result of the proposed system. In the first step, we started the optimization of SOA’s parameters to obtain the optical single-sideband (OSSB) switched signal in order to save bandwidth and reduce the chromatic dispersion (CD) when compared to double-side signal (DSB). Moreover, this optimization aims to produce a high performance of the conversion process and recommend the optimum values of system parameters.

Firstly, in order to obtain an OSSB switched signal with a high sideband suppression ratio (SSR), the injection current of SOA, power of probe, and pump signals are required to be optimized. We run the sweep option with three variables (IC, probe power, and pump power) within the allowed range then we noticed the higher SSR value to assign the optimum value of the three variables. Figure 4(a) displays how the injection current affects SSR. It can be seen that the maximum SSR achieved at 0.6 A of injection current. After that, we investigated the effects of the power of probe and pump signal on SSR, the results are shown in Figures 4(b) and 4(c) respectively. The maximum value of SSR is obtained at 9.45 dBm of probe signal and 8.9 dBm of pump signal.

After this optimization with the aforementioned parameters, the SOA’s optical power spectrum is shown in Figure 5. As seen, the switched signal has an SSR of 22.91 dB which is meaning that the resulted switched signal is an OSSB, not a DSB. In the final step, we investigated the performance of the conversion process by using the OFDM-SPM demodulator on the receiver side. Figures 6(a) and 6(b) display the BER and EVM for the system, both figures show that the performance increased after when the value of OSNR is more than 25 dB.

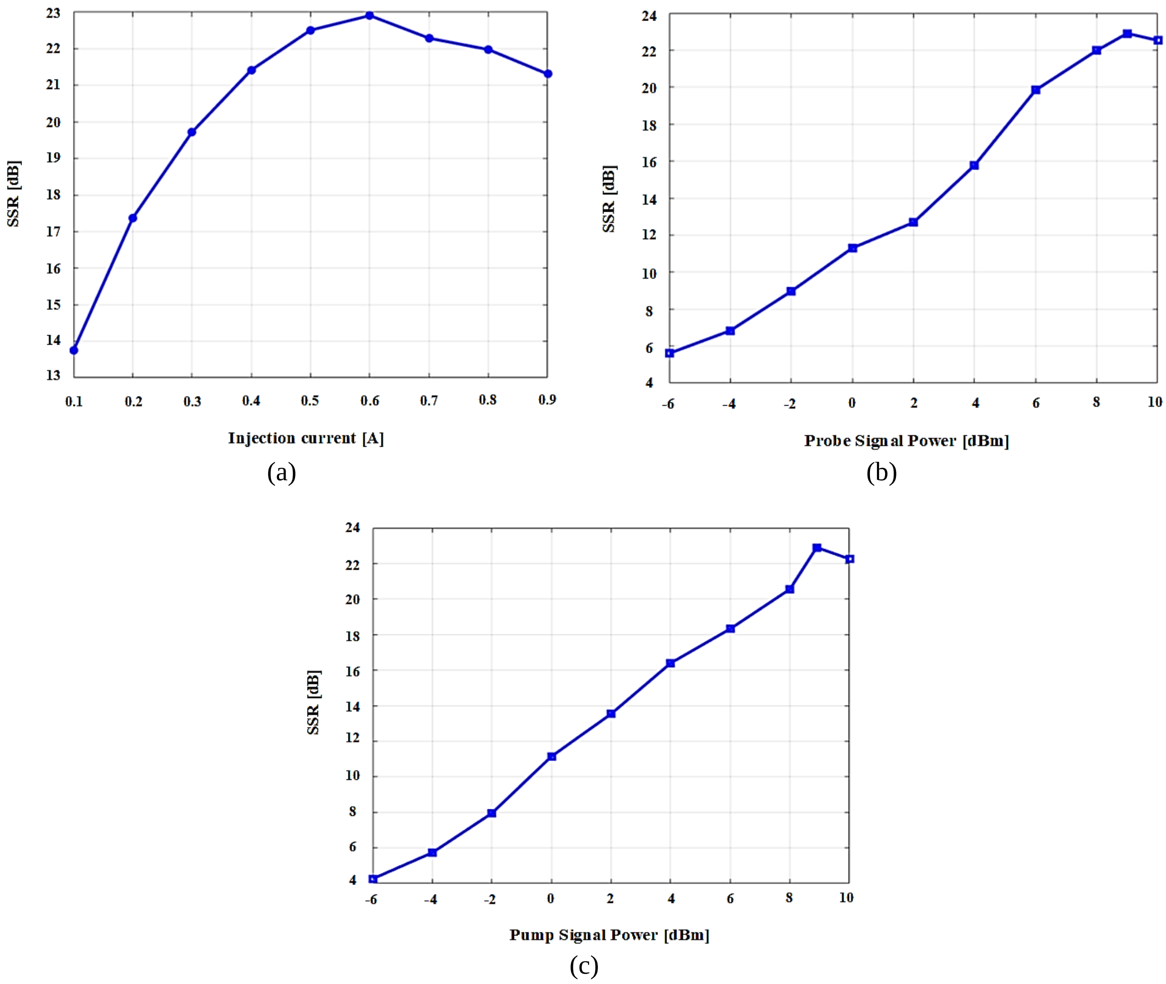


Figure 4. Effects of (a) SOA injection current, (b) probe signal power, and (c) pump signal power, on the SSR

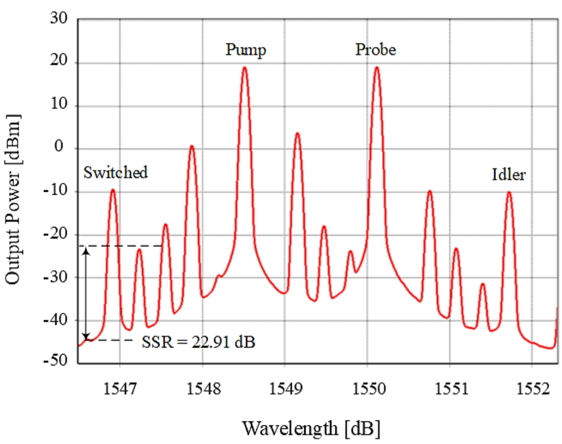
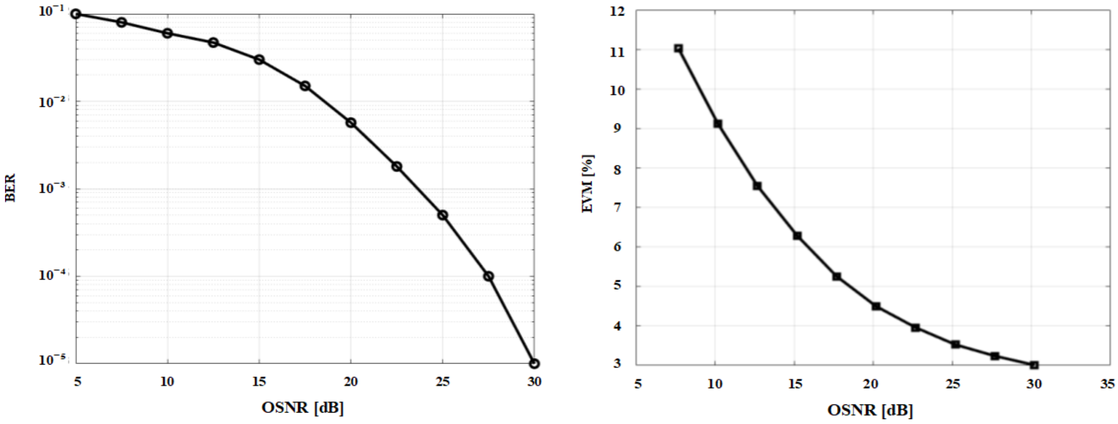


Figure 5. SOA's optical output measured spectrum for ODFM-SPM signal at 80 GHz MMW carrier



(a) (b)

Figure 6. Switching performance in terms of (a) BER and (b) EVM

5. CONCLUSION

This paper demonstrated a photonic system to generate an OSSB signal with E-band carrier frequency and then convert it to the desired wavelength using SOA for OFDM-SPM modulation format. This is done using virtual photonic integrated (VPI) and MATLAB software. The fast response of the nonlinear effect of SOA (i.e., FWM and SPM) provides a fast-switching speed. A 7-Gbps OFDM-SPM signal with a carrier frequency of 80 GHz is converted to a new wavelength and we investigated its performance by the resulted SSR which is 22.91 dB. We optimized the main parameters affecting the SSR such as injection current of SOA, probe power, and pump power. We studied the system's performance in terms of EVM and BER. The results show that OSNR should be more than 25 to get high performance.

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