Modelling and simulation of optical transmitter for 5G passive optical networks

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ABSTRACT

5G is altering the communications future. The 5G literature focuses on wireless and radio technology, but fiber optics play a crucial supporting role in signal transmission to and from the next generation of base stations (BSs) that will serve customers. With the increasing bandwidth requirements of 5G ultra-high-speed applications, passive optical networks (PONs) are the optimal solution. Targeting long-reach 5G PONs, an integrated, high-speed, and cost-effective optical transmitter circuit was constructed and tested. This engine can be combined into a 5G-compliant optical transceiver module. For the purpose of validating the engine performance, a theoretical analysis and an OptiSim™-based design simulation model are carried out. Bit error rate (BER), phase-shifting, and eye diagram were all taken into account when analyzing the transmitter performance. The article findings validate the optical transmitter design. The design is cost-effective and requires no extra components, such as a filter.

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1. INTRODUCTION

The first 5G cellphones will be commercially accessible in 2019, but it will take several years to properly implement the technology. By 2030, 5G services are expected to become widespread and enable communications for applications currently in their infancy, such as virtual reality and autonomous vehicles [1]. Due to 5G's high needs for coverage, bandwidth, and low latency, passive optical networks (PONs) of the subsequent generation will become even more prevalent [2]. Future wireless technology deployment will depend on PONs' smooth connectivity to cloud computing resources and wireless access networks. Combining radio access and PON features into an one convergent platform would help telecom service providers to minimize network complexity, reduce operating costs, improve service quality, better deploy resources across different access technologies, and serve as a catalyst for new markets. [3]. Figure 1 is a simplified representation of 5G PONs.

To address the issue of a lack of spectrum and support multi-gigabit wireless connectivity, 5G uses frequencies above 30 GHz [4]. Due to propagation losses, the generation of these higher frequencies is a difficult process, limiting the transmission distance. For this reason, these frequencies are generated at a center office (CO) and then transmitted to the base station (BS) through the modulation of microwave data signals over an optical carrier. The millimeterwave over fiber (MoF) is the name of this method. The optical domain is superior to its electrical counterpart for generating these higher frequencies due to its superior spectral purity,
reduced equipment requirements, and vast transmission distance [5]. Numerous strategies using optical heterodyning [6]–[10], direct modulation [11]–[14] and external modulation [15]–[20] have been developed for the optical generation of high-frequency signals. External modulation is the most dependable technique; it generates optical harmonics with high-spectral-purity, higher tunability, and stability [21]. In order to keep up with ever-growing bandwidth demands, current optical fiber communications research focuses on boosting the link capacity [22]. Less-complex optical transmitters can boost link capacity [23].

Figure 1. 5G PONs

The aim of this paper is to present a simple optical transmitter design for 5G PONs. There were several factors that were taken into consideration when analyzing the transmitter's performance, such as bit error rate (BER), phase-shifting, and eye diagram of the down-converted signal. The structure of this document is outlined below. Section 2 will go over the transmitter design principles. Section 3 contains the outcomes of computer simulations. Section 4 concludes the paper.

2. METHOD

Figure 2 depicts a schematic diagram of the MoF system configuration, including the proposed optical transmitter. It is obvious that it is divided into three PONs components: optical line terminal (OLT), optical distribution network (ODN), and optical network unit (ONU). The OLT is a central office device that serves as the starting point for the PONs, which are connected to a core switch via Ethernet cables. The OLT's primary responsibility is to convert frames and send data for the PON.

Figure 2. MoF system

PON data can't be sent without ODN, which directly affects a PON system's performance, reliability, and ability to grow. The ODN is a component of the PON system and serves as the physical path along which

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light travels from the OLT to the ONT. Its range is at least 20 km. Optical fibers, optical splitters, and fiber optic connectors work together in the ODN. An ONU is a device that transforms signals sent through fibers from optical to electrical. Then, these signals are sent to specific customers. In addition, the ONU is capable of transmitting, aggregating, and preparing various forms of client data for transmission to the OLT.

The proposed optical transmitter consists of two parallel single-electrode mach-zehnder modulators (SEMZMs) [24]. An optical splitter divides the injected lightwave into two parcels. Each parcel is assigned an SEMZM. Both SEMZMs must be biased at the maximum transmission bias point (MTBP) with $\phi=45^\circ$ separating RF driving signals. Using an optical spectrum analyzer, the outputs of A and B are only even optical harmonics, as shown by the solid arrows in Figure 3. The index of modulation is 2.4. So, when the powers of two $2^{nd}$ optical harmonics at the outputs of A and B are combined at the output of the optical transmitter, they make two $2^{nd}$ optical harmonics with double the power, as shown in Figure 3. An oscilloscope is used to get a high-quality OCS signal with $4^{th}$ times the frequency of radio frequency (RF) driving signals.

![Waveguide](image)

**Figure 3. Proposed optical transmitter**

The output field of the SEMZM A or SEMZM B is given by:

$$\xi_A = \xi_B = (\gamma e^{j\phi_1} + (1 - \gamma)e^{j\phi_2}) = (\gamma e^{j\phi_1} + (1 - \gamma)e^{j\phi_2}) = \left(\frac{1}{2} e^{j\frac{\pi}{V_{\pi}}V_1} + \frac{1}{2} e^{j\frac{\pi}{V_{\pi}}V_2}\right)$$

(1)

where $\phi_l, \phi_v, V_1$, and $V_2$ are phases and driving signals to electrode 1 and electrode 2 of SEMZM A, $\gamma$ is the splitting ratio = $\frac{1}{2}$ and $V_5$ is the $\pi$-phase difference:

$$\frac{e^{j\frac{\pi}{2V_{\pi}}(V_1+V_2)}}{2}, \left(e^{j\frac{\pi}{2V_{\pi}}(V_1-V_2)} + e^{-j\frac{\pi}{2V_{\pi}}(V_1-V_2)}\right) = e^{j\frac{\pi}{2V_{\pi}}(V_1+V_2)}.\cos[(\pi/2V_{\pi}).(V_1 - V_2)]$$

(2)

with $V_2 = -V_1$, the (2) become:

$$\xi_A = \xi_B = \cos\left(\frac{\pi}{V_{\pi}}V(t)\right) = \cos\left[\frac{\pi}{V_{\pi}}(V_{\text{bias}} + V_m\cos(\omega_gt))\right]$$

(3)

as SEMZM A is operated at the MTBP (i.e., $V_{\text{bias}}=0$), only even optical harmonics are observed. Expanding the (3) using Bessel functions, $\xi_i$ can be rewritten as [25]:

$$\xi_{A(MTBP)} = g_0 \cos(\omega_ct) + g_2 \cos(\omega_ct + 2\omega_mt) + g_2 \cos(\omega_ct - 2\omega_mt)$$

(4)

as SEMZM A is operated at the MITBP (i.e., $V_{\text{bias}}= V_3$), only odd optical harmonics are observed. $\xi_i$ can be rewritten as [25]:

$$\xi_{A(MTBP)} = g_1 \cos(\omega_ct + \omega_mt) + g_1 \cos(\omega_ct - \omega_mt)$$

(5)

where $\omega_c$, $\omega_b$ are the continuous wave (CW) and driving signal frequencies, respectively, and, $g$ is the $n$th order Bessel function of the first kind. The output field of the optical modulator is given by:

$$\xi_{out} = \xi_{A(MTBP)} + \xi_{B(MTBP)} \cdot \xi_c = \xi_{A(MTBP)} + \xi_{B(MTBP)} \cdot 1 = \xi_{A(MTBP)} + \xi_{B(MTBP)}$$

(6)
the driving signals sent to A and B modulators are:

\[ V_A = V_D \sin(\omega_D t) \]  \hspace{1cm} (7)

\[ V_B = V_D \sin(\omega_D t + 45^0) \]  \hspace{1cm} (8)

where \( V_D \) is the amplitude of the driving signal. The modulated output lightwave can be expressed as:

\[ \xi_A = g_0 \sin(\omega_C t) + g_2 \sin(\omega_C t + 2\omega_D t) \]  \hspace{1cm} (9)

\[ \xi_B = g_0 \sin(\omega_C t) + g_2 \sin(\omega_C t - 2\omega_D t) \]  \hspace{1cm} (10)

with index of modulation=2.4, the (6) can be written as:

\[ \xi_{out} = g_2 \sin(\omega_C t + 2\omega_D t) + g_2 \sin(\omega_C t - 2\omega_D t) \]  \hspace{1cm} (11)

3. RESULTS AND DISCUSSION

To verify the transmitter performance, Optisystem is used to simulate the MoF system (Figure 2). Optisystem is a simulation software that is utilized for the purposes of planning, testing, and optimizing the performance of optical networks. Table 1 displays the values of the simulated MoF system parameters.

| Component          | Parameter | Values |
|--------------------|-----------|--------|
| Extinction Ratio   | ER        | 25 dB  |
| Half-wave voltage  | \( V_\pi \) | 4 volt |
| Responsivity       | \( \mu \) | 0.7 A/W |
| Noise Figure       | NF        | 5 dB   |
| Thermal noise      | F         | \( 10^{-12} \) A/Hz\( ^{0.5} \) |
| Insertion loss     | \( \alpha \) | 5 dB   |
| Fiber length       | L         | 60 km  |

Figures 4-6 depict the eye diagrams of the down-converted signal from the SMF for different fiber lengths (10, 30, and 60 km). The eye diagram was displayed on the eye diagram analyzer, which functioned like an oscilloscope. It can be seen that the shape of the eye patterns changes slightly, but the eye patterns are still clear and stay open even when optical signals are sent over 60 km.
The effect of phase-shifting on the amplitude of the sideband suppression ratio is depicted in Figure 7. The phase shift between RF driving signals is varied between 0° and 15°. Figure 7 shows that for a phase shift near the ideal value, i.e., 0°, the highest amplitude of sideband suppression can be obtained. The value then decreases slightly as the phase shift value increases. If the deviation is less than 10 dB, an amplitude of 15 dB can be obtained. That should suffice for the majority of MoF applications [26].

Figure 8 shows the relationship between simulated BER and fiber length. At a data rate of 5 Gbit/s, two effective input light power values (P_r = 0 and P_r = 5 dBm) were taken. The BER is approximately 10^{-25} when the light power is P_r = 0 dBm and the transmission distance is 60 km. The MoF system has a high BER value (BER ≥10^{-12}) when the effective light power is dropped to 5 dBm. Increased fiber length, attenuation, and dispersion all contribute to increased BER. Figure 9 illustrates the B-T-B (0 km) and 30 km BER simulations as a function of the received power at a data rate of 5 Gbit/s. The penalty is around 0.65 dB when the BER is 10^{-10}. Fiber propagation loss is responsible for the diminished signal strength.
4. CONCLUSION

PONs will play a critical role in the 5G era. Implementing a simple optical transmitter is one strategy for increasing PONs capacity. This work provides a simple and cost-effective optical transmitter architecture based on two parallel SEMZMs and evaluates its performance numerically and via simulation. The effects of phase shift variation on the amplitude of the sideband suppression ratio, variation of fiber length, and received power on the BER were all explored. At the receiver, clear eye patterns could be seen. Based on the article findings, the proposed optical transmitter has enhanced performance, a low cost, and a simple configuration.

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