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Generation of Optical Carrier Suppressed Signal for Radio-over-Fiber (RoF) System Using Dual-Drive Mach-Zehnder Modulator

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Abstract- This paper presents the generation of optical carrier suppressed signal for RoF system. RoF refers to an analog transmission over fiber technology where light is modulated by radio frequency (RF) signal and transmitted over an optical fiber link to wireless access. Both optical carrier suppression and signal modulation are made by using a Dual-Drive Mach-Zehnder modulator (DD-MZM). Suppressed carrier modulation is achieved by biasing at the null point of DD-MZM. Optical carrier suppression improves the performance of RoF system such as link gain and noise figure (NF).In this research, a single RF at 2100 MHz having data rate of a 1 Gbps modulates the 1550.12 nm optical carrier in the DD-MZM. In this paper, the carrier suppression and performances of RoF system are investigated by theory and simulation. The various values of optical carrier suppression ratio can be obtained by adjusting the extinction ratio of the DD-MZM. The transmission performance of the proposed system is verified by the simulation results.

Index Terms- Optical carrier suppression, Dual-Drive Mach-Zehnder modulator (DD-MZM), Single Mode Fiber (SMF), Radio-over-Fiber (RoF) system.

I. INTRODUCTION

The RoF is a technology used to distribute RF signals over analog optical links. In such RoF system, radio frequency (RF) signals are modulated onto an optical carrier at a central station (CO) and then transported to remote sites or base stations (BS) using optical fiber. The BS then transmits the RF signal over small signal areas using microwave antennas. Radio-over-Fiber (RoF) system are widely applied in applications because of lightweight, low loss, high capacity and high immunity to electromagnetic interferences [1-2]. In RoF system, although the optical carrier does not contain any information, it consumes most of the total optical power in quadrature-biased modulation link. Therefore, optical carrier power is essentially suppressed to improve performances of RoF link. The factors of performances of RoF link include link gain and noise figure (NF). Carrier suppression significantly reduces the noise contributions such as noise figure, thermal noise and shot noise [3]. Mach-Zehnder modulators are used to generate optical RF signal with double-sideband and carrier suppression [4]. Optical carrier suppression causes frequency doubling [5]. Many approaches are used to suppress undesired optical carrier such as low biasing Mach-Zehnder modulator [6], optical carrier filtering [7] and Stimulated Brillouin scattering [8].

Among them, low biasing Dual-Drive Mach-Zehnder modulator (DD-MZM) has been chosen in this research. Mach-Zehnder modulator has demonstrated to be a good carrier suppression but more input optical power is needed to keep the same modulation efficiency. The optical carrier suppression with DD-MZM has been used for both frequency upconversion and signal modulation. The important factor of carrier suppression ratio is the extinction ratio (ER) of DD-MZM.In this paper, optical carrier suppression, improvement of performances and generation of microwave baseband signal in RoF system are analyzed by the simulated signal waveforms, optical carrier-suppressed spectrum and bit-error-rate measurement. The simulation results are carried out by using Optisystem software.

II. THEORETICAL ANALYSIS OF MICROWAVE (MW)SIGNAL GENERATION BY OPTICAL CARRIER SUPPRESSION

A.Generation of MW Signal and Optical Carrier Suppression using DD-MZM Analysis

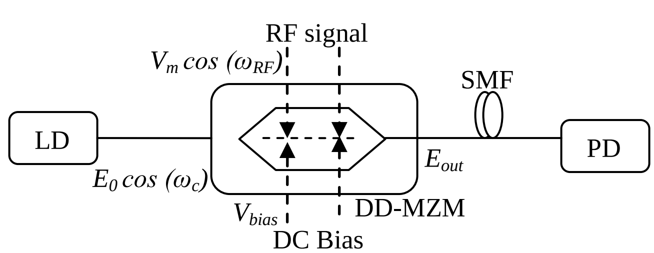


Fig. 1. The principle of optical carrier suppression and generation of MW signal.

Fig. 1 shows the principle of optical carrier suppression and generation of MW signal. Suppressed carrier modulation is achieved by biasing a DD-MZM such that the optical carrier components cancel at the output of the modulator. The power splitting ratio of both arms of DD-MZM is $r_1 = r_2 = 0.5$. An optical carrier out of one arm of the DD-MZM is expressed as

$$E_{out}(t) = E_0 \cos[\pi V(t)/2V_\pi]\cos(\omega_c t) \tag{1}$$

where E_0 and ω_c are the amplitude and angular frequency of the input optical carrier, respectively, $V_л$ is the half-wave voltage of the DD-MZM and $V(t)$ is the applied driving voltage. The loss of DD-MZM is neglected. $V(t)$ consisting of an electrical sinusoidal signal and a dc biased voltage is given by

$$V(t) = V_{bias} + V_m \cos(\omega_{RF} t) \tag{2}$$

where V_{bias} is the dc biased voltage, V_m and ω_{RF} are the modulation voltage and the angular frequency of electrical driving signal, respectively. Therefore, the output of the DD-MZM converted from exponentials to sinusoidal results in

$$\begin{aligned} E_{out}(t) &= E_0 \cos(\pi/2[V_{bias}/V_\pi + V_m/V_\pi \cos(\omega_{RF} t)])\cos(\omega_c t) \\ &= E_0 \{\cos x.\cos[m\cos(\omega_{RF} t)] - \sin x.\sin[m\cos(\omega_{RF} t)]\}\cos(\omega_c t) \end{aligned} \tag{3}$$

Where $x = (V_{bias}/2V_\pi)\pi$ is a constant phase shift that is induced by the dc biased voltage, and $m = (V_m/2V_\pi)\pi$ is the phase modulation index. Equation (3) is expanded by using Bessel functions as detailed in Appendix I.

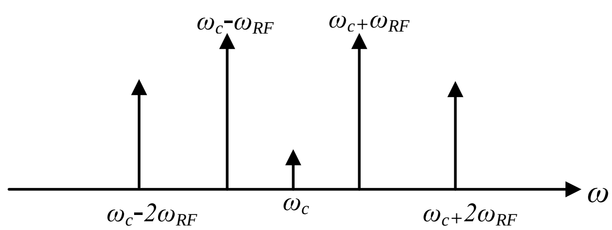


Fig. 2. The optical spectrum of the MW signals

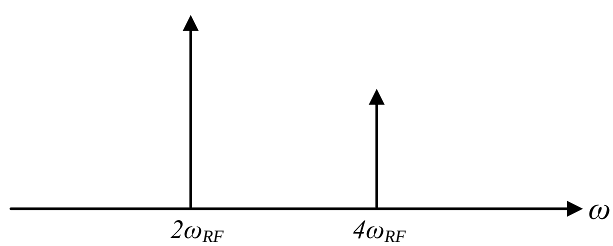


Fig. 3 Illustration of the electrical spectrum of generated MW signal using DD-MZM after PD detection.

Fig. 2 shows the optical spectrum of the MW signal obtained by optical carrier suppression modulation with the DD-MZM biased at the null point. After being detected by the photo-diode (PD), the electrical spectrum of the generated MW signal is achieved. Fig. 3 presents transmission electrical spectrum of the generated MW signal. The double-frequency signal ($2\omega_{RF}$) and the even terms of the harmonic distortions are observed.

B. Operation and Transfer Function of DD-MZM

The most popular modulator in optical communication systems is the Lithium Niobate ($LiNbO_3$) MZM. There are two types of MZM: single drive MZM and dual-drive MZM. The optical wave enters from the input side and then splits equally into two arms. The structure of the dual-drive MZM has two arms and electrodes. Data and inverted data are used by the DD-MZM to generate the intensity modulation. The modulation voltages are applied to both arms of the interferometer and phase changes of ± л/2 in the arms of the interferometer. When operating the DD-MZM at the appropriate bias null point or minimum point, optical carrier-suppressed signal exits the output port. When the DD-MZM is biased at the quadrature point, the information carrying sidebands with optical carrier exit the output port. The RF-driven signals are applied to the two arms with different phase shifts and the two arms are biased by different DC voltages. The optical phase in each arm can be controlled by changing the voltage applied on the electrode. The transfer function of MZM is shown in Fig. 4 for optical carrier power suppression and double frequency generation.

The DD-MZM suppresses undesired optical carrier power. To suppress optical carrier power, the modulation is biased at the null point. These optical carrier power can degrade the performance of RoF system such as link gain and noise figure (NF). Thus, undesired optical carrier power needs to be suppressed. The bias voltage modulates at the null point to suppress undesired carrier power and then not only increased link gain but also reduced noise figure will be improved by the bias voltage. This performances relate to the bias voltage, as shown in Appendix I. Moreover, the more the value of ER, the more the power splitting ratio. The power splitting ratio of DD-MZM will be 0.5 when the ER is 30 dB. This is the best condition to suppress undesired carrier power. The MW signal is produced by optical carrier suppression modulation, the two first-order sidebands are the desired optical signals and the undesired optical carrier suppression are the key parameter in the RoF system. The Optisystem software is used to simulate the carrier suppression and generation of MW signal.

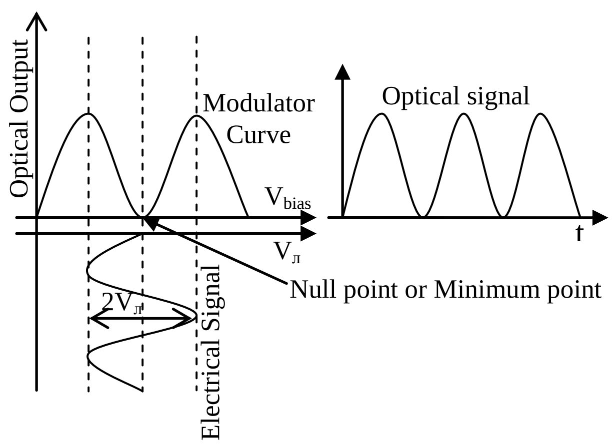


Fig. 4. The transfer function of Mach-Zehnder Modulator

III. Simulation of Carrier Suppression in RoF System

A. Simulation Setup for the Proposed System

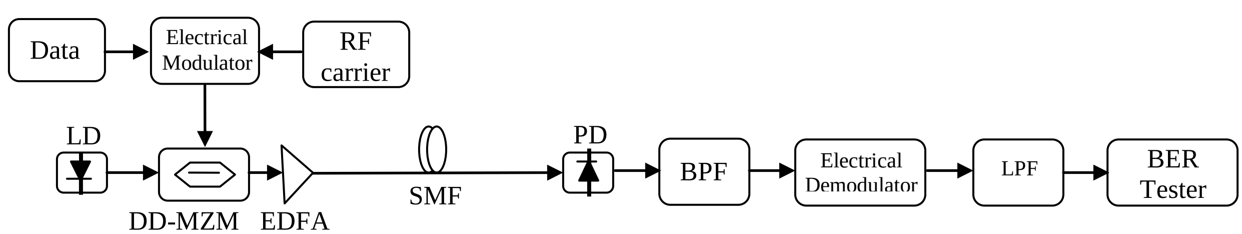


Fig. 6. The simulation setup of the RoF system for optical carrier suppression.

Fig. 6 illustrates the simulation setup of the RoF system with the carrier suppression using DD-MZM. The continuous wave is generated by a laser with a wavelength at 1550.12 nm. The radio frequency (RF) signal is generated by amplitude modulating 2100 MHz RF signal by 1 Gbps pseudorandom bit sequence data stream. The optical signal is modulated by the RF signal in the DD-MZM. The MZM is biased at the minimum transmission point and driven with 2100 MHz sine waves having a peak-to-peak amplitude of $2V_л$ (driving voltage). The $V_л$ of the DD-MZM is 4 V at direct current (DC) frequency. The biased voltages are 0 V to 4 V ranges. The frequency difference of two optical sidebands is twice the frequency of the electrical driving signal after optical carrier power is suppressed at the DD-MZM. And then, the generated optical signal is amplified by using an erbium-doped fiber amplifier (EDFA) with 10 dB gain but the amplified spontaneous emission (ASE) noise was generated by EDFA. The optical signal is transmitted over 8-km SMF. After it is transmitted over 8-km SMF, the optical signal is converted to electrical signal by using PD at the BS and then the output is filtered by band-pass filter (BPF) with 4200 MHz. After filtering, the output is amplified by using an electrical amplifier. Finally the output electrical signal is demodulated by electrical demodulator and then a low-pass filter (LPF) is employed to reject the undesired RF components and then the baseband signal is analyzed by a bit-error-rate (BER) tester.

B. Simulation Results and Discussion

The RF wave will be at 2100 MHz at the transmitter. A CW lightwave was generated by a laser diode (LD) with a wavelength of 1550.12 nm and modulated with DD-MZM is driven by the RF signal. The DD-MZM is biased at the null or minimum transmission point to realize optical carrier suppression modulation. The optical waveforms and spectra after the DD-MZM are shown in Fig. 7. The optical carrier suppression ratio is around 5 dB and then the optical signal was transmitted over 8-km single mode fiber (SMF). At the BS, the output optical signal is detected by PD to convert into electrical signals, as shown in Fig. 8.

The optical MW signal is achieved by using DD-MZM that adjusts the bias voltage and the extinction ratio. When the DD-MZM ER is 30 dB, the carrier suppression ratio will be the best. More ER is needed to increase the carrier suppression ratio. As the ER falls from 30 to 15, optical carrier suppression ratio (OCSR) decreases from 5 to 1.3 dB, as shown in Fig. 10. Fig. 11 presents the extinction ratio (ER) versus the carrier suppression ratio following 8-km transmission of SMF. As the DD-MZM ER falls, the carrier suppression ratio decrease. When the DD-MZM ER is 30 dB, the carrier suppression ratio is 5 dB and the receiver sensitivity of the MW signal is acceptable.

The performance of RoF system is related to the optical carrier power which can be suppressed by using DD-MZM. The optical carrier suppression depends on the extinction ratio. If extinction ratio is increased, the optical carrier suppression ratio will be increased by using DD-MZM. The Q-factor initially can also increase and then decrease as ER falls from 30 to 10, as shown in Fig. 12, and the BER is the best at the optimal ER of 30. The bit-error-rate (BER) is measured for baseband signal, both back-to-back and over the fiber as shown in Fig. 13. After the optical RF signal is transmitted over 8-km SMF, the power penalty at BER of 10^{-9} is 4.356 dBand Q-factor value is 5.63564.The Q-factor value of Back-to-Back case at the output of transmitter is 5.69845.

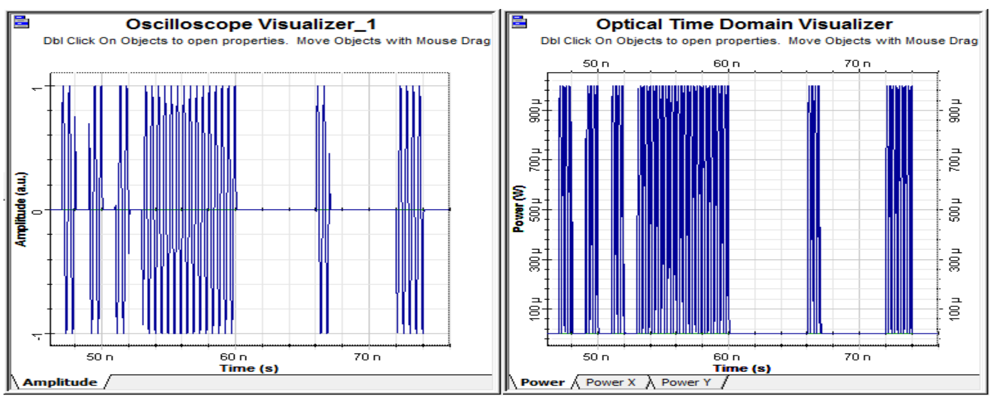
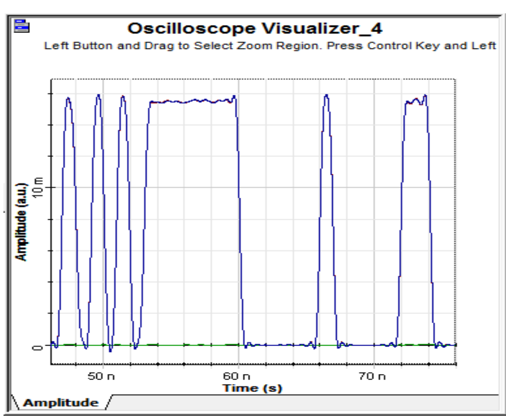


Fig. 7. The optical signal waveform and the carrier suppression spectrum at MZM output



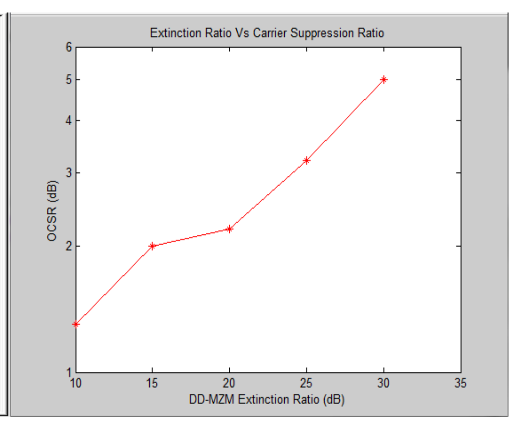
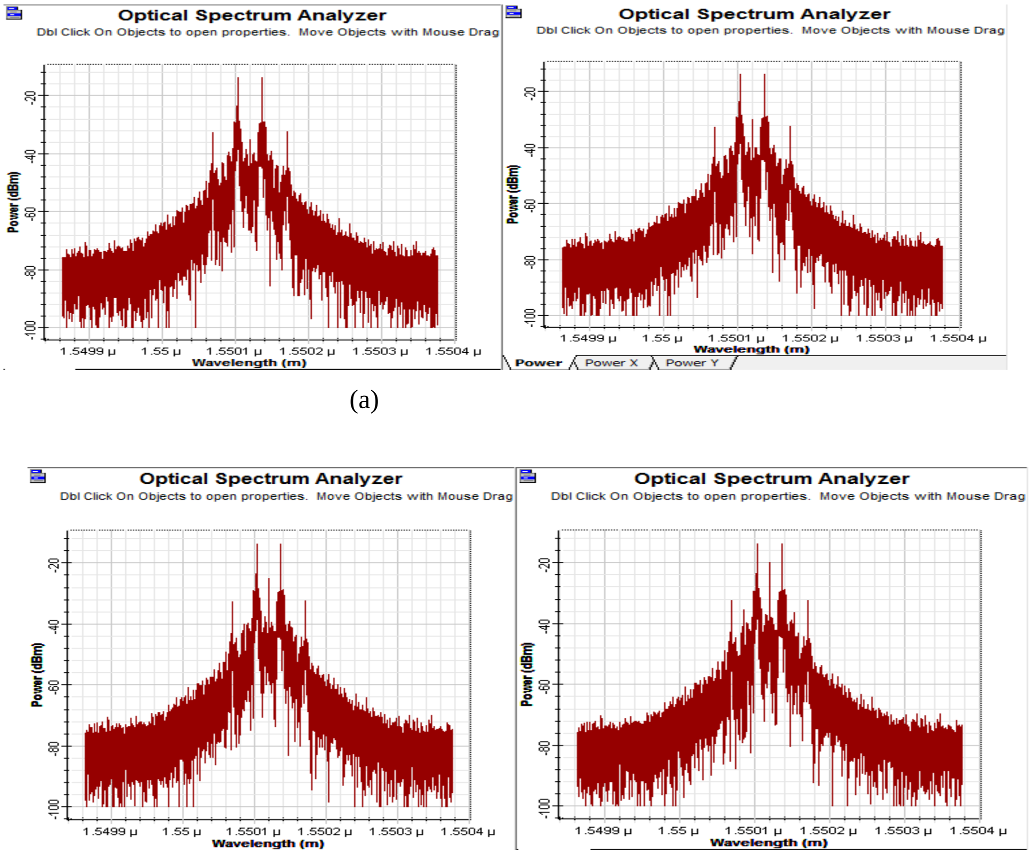


Fig. 8. The PD output RF signal

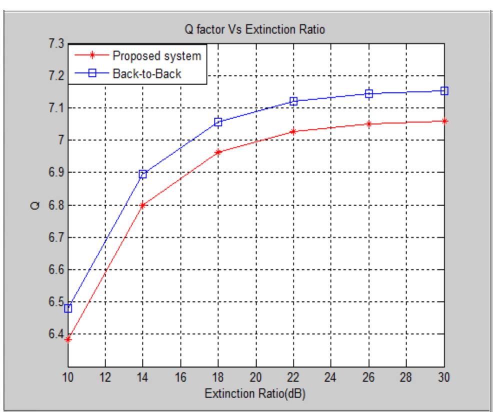
Fig. 9. The Extinction ratio and the optical carrier suppression ratio



(a) (b)

(c) (d)

Fig. 10. The spectrum of optical carrier suppression with ER is set at (a) 30 dB, (b) 25 dB, (c)20 dB, and (d)15 dB.



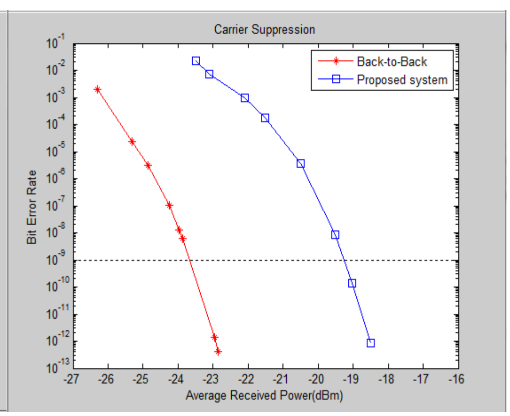


Fig. 11. Q-factor Vs Extinction RatioFig. 12. BER curves of optical microwave signals after transmission over 8-km SMF and BTB.

IV. CONCLUSION

The generated electrical MW signal, performances of RoF system and optical carrier suppression was investigated with the simulation. The performance of RoF system and the optical carrier suppression using DD-MZM was theoretically studied. Moreover, the Q-factor, extinction ratio (ER) and power splitting ratio have been also discussed. According to the simulation results, more extinction ratio of DD-MZM is required for better carrier suppression.

Appendix I

Equation (1) is expanded with Bessel function at the output of the DD-MZM as

$$E_{out}(t) = E_0 \cos x \begin{Bmatrix} J_0(m)\cos(\omega_c t) \\ + \sum_{n=1}^{\alpha} \begin{bmatrix} J_{2n}(m)\cos(\omega_c t + 2n\omega_{RF} t - n\pi) \\ + J_{2n}(m)\cos(\omega_c t - 2n\omega_{RF} t + n\pi) \end{bmatrix} \end{Bmatrix}$$
$$+ E_0 \sin x \begin{Bmatrix} \sum_{n=1}^{\alpha} \begin{bmatrix} J_{2n-1}(m)\cos(\omega_c t + (2n-1)\omega_{RF} t - n\pi) \\ + J_{2n-1}(m)\cos(\omega_c t - (2n-1)\omega_{RF} t + n\pi) \end{bmatrix} \end{Bmatrix} \quad \text{(A1)}$$

where J_n is the Bessel function of the first order n. The first term in this equation is the carrier component, and the secondand third terms are the odd and even-order sidebands respectively. If the bias voltage is equal to the driving voltage, $V_{bias} = V_\pi$, cos x = 0 and sin x = 1 because of $x = (V_{bias}/2V_\pi)\pi$. So,the output of DD-MZM with the optical carrier suppression can be written as

$$E_{out}(t) = E_0 \left\{ \sum_{n=1}^{\alpha} \left[J_{2n-1}(m)\cos(\omega_c t + 2n\omega_{RF} t - n\pi) + J_{2n-1}(m)\cos(\omega_c t - (2n-1)\omega_{RF} t + n\pi) \right] \right\} \quad \text{(A2)}$$

After suppressing the carrier power, the performances of RoF system is improved. In external modulation , the link gain can be expressed as

$$G_{link} = 10\log\left\{ P_i \left[\sin\left(\frac{\pi V_{bias}}{2V_\pi}\right) \frac{\pi \Re}{2V_\pi} \right]^2 \times R_{\mathrm{mod}} \times R_D \right\} \quad \text{(A3)}$$

where G_{link} is link gain, P_i is the CW input optical power to the modulator, V_π is the modulator driving voltage, $\Re$ is photo-diode responsivity, R_{mod} is modulator load resistance and R_D is photo-diode resistance. After detection using PD, the photocurrent can be expressed as

$$I_D = T_{ff} T_{\mathrm{mod}} \Re P_i \quad \text{(A4)}$$

where T_{ff} is fiber loss and T_{mod} is modulator loss. Noise figure includes shot noise and relative intensity noise (RIN). RIN can neglected as the optical carrier power is suppressed. The relation of noise figure and shot noise can be written as

$$NF = 10\log\left(2 + \frac{2qI_D R_{\mathrm{mod}}}{G_{link}\kappa T} \right) \quad \text{(A5)}$$

where q is electric charge (±1.602*10^-19), K is Boltzmann's constant (1.38*10^-23) and T = 290̊K.

The optical carrier suppression will improve the performance of RoF link. The improvement of link gain depends on the biased voltage. When the link gain is increased, the noise figure will decrease. When the biased voltage is 4 V at the null point modulation, the link gain is -36 dB with carrier suppression. When the biased voltage is 2 V at the quadrature point modulation, the link gain is -42 dB without carrier suppression. The values of noise figure are 31 dB with carrier suppression and 37 dB without carrier suppression. These performances are theoretically investigated. The link gain and noise figure depend on the bias voltage.

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