第 45 卷第 6 期　　红外与激光工程　　2016 年 6 月
Vol.45 No.6　　Infrared and Laser Engineering　　Jun. 2016

Study on a radio over fibre link with improved receiver sensitivity based on polarization modulation

Li Jing[1,2], Ning Tigang[1,2], Pei Li[1,2], Jian Wei[1,2], Zheng Jingjing[1,2], You Haidong[1,2,3], Wen Xiaodong[1,2]

(1. Key Lab of All Optical Network & Advanced Telecommunication Network of EMC, Beijing Jiaotong University, Beijing 100044, China;
2. Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China;
3. Science and Information College, Qingdao Agricultural University, Qingdao 266109, China)

Abstract: In this work, a radio over fibre link with improved receiver sensitivity was reported. The basical mechanism of this prototype was to realize optical single sideband modulation with an optimum optical carrier-to-sideband ratio (OCSR). To do this, both polarization modulation and optical interleaving technology were employed. The linearly polarized incident light was firstly oriented at an angle of $\alpha(\alpha\neq 0°$ or $90°)$ relative to one principal axis of the polarization modulator (PolM), which is biased by V_π and driven by RF signals. Then a polarizer with its polarization direction β $(\beta\neq 0°$ or $90°)$ relative to one principal axis of the PolM was used to linearize the polarization state. Finally, optical double sideband signal was converted to optical single sideband signal by using a standard optical interleaver. It is found the OCSR is only dependent on the values of two polarization angle, α and β. With careful adjustment, the OCSR can be reduced to 0 dB, which is the optimum value for a single RF tone modulation. The receiver sensitivity of the fibre link is analyzed by theory and then verified by simulation. It can be greatly improved by using this technique.

Key words: microwave photonic;　radio-over-fibre link;　receiver sensitivity;
optical single sideband modulation;　optical carrier-to-sideband ratio

CLC number: TN929.11　　**Document code:** A　　**DOI:** 10.3788/IRLA201645.0617004

基于偏振调制的最优接收灵敏度的 ROF 链路研究

李　晶[1,2]，宁提纲[1,2]，裴　丽[1,2]，简　伟[1,2]，郑晶晶[1,2]，油海东[1,2,3]，温晓东[1,2]

(1. 北京交通大学 全光网络与现代通信网教育部重点实验室，北京 100044；
2. 北京交通大学 光波技术研究所，北京 100044；
3. 青岛农业大学 科学与信息学院，山东 青岛 266109)

摘　要：提出了一个基于偏振调制的最佳接收灵敏度 ROF 链路系统。其根本原理在于实现具有最佳光载波边带比(OCSR)的光单边带调制技术，为此，利用偏振调制和滤波技术，线偏光首先经由一个特定偏振角 α 进入偏振调制器，然后一个固定起偏角 β 的起偏器被用来合并偏振信息，最后利用一个

收稿日期：2015-10-12；　**修订日期**：2015-11-15

基金项目：国家自然科学基金(61405007)；北京市自然科学基金(4154081)；北京交通大学人才基金(2014RC027)

作者简介：李晶(1984-)，男，讲师，博士，主要从事微波光子学方面的研究。Email:lijing@bjtu.edu.cn

光滤波器实现光双边带调制到光单边带调制的转换。研究发现所获得的OCSR只与两个偏振角(α和β)有关,通过仔细调节上述指标,可以将OCSR调谐至最佳值0 dB。利用仿真验证了上述结论,仿真发现通过将OCSR调谐至最佳值将大大提高ROF链路的接收灵敏度。

关键词: 微波光子; 微波光子链路; 接收灵敏度; 光单边带调制; 光载波边带比

0 Introduction

Radio over fibre(RoF) system has been considered as a promising solution to the last mile connection problem in the next generation wireless communication system [1-2]. Different from the traditional wireless communication system, one typical RoF system uses fibre links to connect one central station (CS) and several base stations (BSs). At the BSs, lightwave signals are then converted to electrical signals and then transmitted to multiple mobile devices. When considering the fibre links connecting the CS and BSs, chromatic dispersion is the primary concern. Optical double sideband modulation (ODSB) will lead to periodic power fading of the converted RF signals, which will lead to serious power penalty of fibre links transmission. Normally, this problem can be solved by using adaptable dispersion compensators. Several techniques have been reported, such as the approaches using midway optical phase conjugation, pre-compensation in electrical domain with phase shifting, carrier phase-shifted double sideband (OCS-DSB) modulation and mixed polarization modulation. But in a practical RoF system, there are hundreds of fibre links which need to be compensated. It will increase the cost of construction and maintenance. Optical single sideband (OSSB) modulation seems to be a good solution to remove fibre dispersion-induced power fading[3-4]. With an optimum optical carrier-to-sideband ratio (OCSR), it can also improve the receiver sensitivity of fibre links. So far, lots of techniques have been reported. In Ref. [5], fibre Bragg grating (FBG) was used to improve link performance. By suppressing optical carrier via a narrow-band FBG, the OCSR is decreased and the receiver sensitivity is improved consequently. Then in Ref. [6], a chirped fibre grating with triangular-shaped spectrum was used to remove one sideband from the ODSB signal and reduce the OCSR simultaneously. As a matter of fact, a tunable OCSR is also important. There are two reasons to this issue: (1) the modulation index varies in practice, thus a continuous tunability of the OCSR maybe helpful to realize the optimum OCSR. (2) when considering the sub-carrier multiplication (SCM) technique, the optimum OCSR is supposed to be different with respect to different RF tones[7].

In this work, a RoF link with improved receiver sensitivity is proposed and analyzed. The key component is a polarization modulator(PolM) followed by a linear polarizer (LP). According to the analysis, the target OCSR can be tuned by adjusting two polarization angles, α and β. Thus the proposal might be attractive since it requires only two polarization controllers(PC) to do the OCSR's tuning.

1 Theory

Figure 1 shows the schematic setup of the proposed RoF link based on polarization modulation. The dash pane consists of one PolM, one LO, two PCs and one LP. The key component, PolM, is a special phase modulator that supports transverse

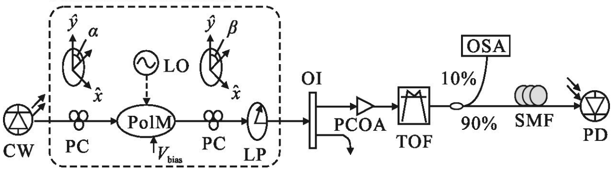

Fig.1 Schematic setup of the proposed RoF link based on polarization modulation

electric(TE) and transverse magnetic(TM) modes with complementary phase modulation indices. Assuming the incident light is oriented at an angle of α ($\alpha\neq 0°$ or 90°) relative to one principal axis of the PolM ($\hat{y}$), the output optical field can be expressed as :

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto \begin{bmatrix} \sin\alpha\exp(j\omega_0 t+jm\cos\omega_{\rm RF}t+j\varphi) \\ \cos\alpha\exp(j\omega_0 t-jm\cos\omega_{\rm RF}t) \end{bmatrix} \tag{1}$$

where ω_0 is angular frequency of optical carrier, m is modulation index, $\varphi=\pi V_{\rm bias}/V_\pi$ is bias-induced phase shift, and V_π denotes half-wave voltage of the PolM. Under small signal modulation, Eq.(1) can be simply concluded as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto \begin{bmatrix} \sin\alpha\sum\limits_{n=-1}^{1} j^n J_n(m)\exp(j\omega_0 t+jn\omega_{\rm RF}t+j\varphi) \\ \cos\alpha\sum\limits_{n=-1}^{1} j^n J_n(-m)\exp(j\omega_0 t+jn\omega_{\rm RF}t) \end{bmatrix} \tag{2}$$

where J_n is the Bessel function of the first kind of order n. Then an OBPF is employed to remove one sideband of the signal in Eq.(2). It becomes

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto \begin{bmatrix} \sin\alpha[J_0(m)\exp(j\omega_0 t+j\varphi)+jJ_{-1}(m)\exp(j\omega_0 t-j\omega_{\rm RF}t+j\varphi)] \\ \cos\alpha[J_0(-m)\exp(j\omega_0 t)+jJ_{-1}(-m)\exp(j\omega_0 t-j\omega_{\rm RF}t)] \end{bmatrix} \tag{3}$$

Finally, an LP with its principle polarization direction β ($\beta\neq 0°$ or 90°) relative to $\hat{y}$ is employed. Optical field becomes

$$E_{\rm out}(t)=\sin\beta E_x+\cos\beta E_y=\sum_{n=-1}^{0} a_n\exp(j\omega_0 t+jn\omega_{\rm RF}t) \tag{4}$$

In Eq.(4), α_n stands for

$$\alpha_n=\begin{cases} \sin\alpha\sin\beta J_0(m)\exp(j\varphi)+\cos\alpha\cos\beta J_0(m), & n=0 \\ -j\sin\alpha\sin\beta J_1(m)\exp(j\varphi)+j\cos\alpha\cos\beta J_1(m), & n=-1 \end{cases} \tag{5}$$

The OCSR can be calculated as

$$\text{OCSR}=\frac{|\alpha_0|^2}{|\alpha_{-1}|^2}=\frac{J_0^2(m)[(\sin\alpha\sin\beta)^2+(\cos\alpha\cos\beta)^2+2\sin\alpha\cos\alpha\sin\beta\cos\beta\cos\varphi]}{J_1^2(m)[(\sin\alpha\sin\beta)^2+(\cos\alpha\cos\beta)^2-2\sin\alpha\cos\alpha\sin\beta\cos\beta\cos\varphi]} \tag{6}$$

When $\varphi=\pi V_{\rm bias}/V_\pi=180°$ is satisfied ($V_{\rm bias}=V_\pi$), Eq.(6) can be simplified to

$$\text{OCSR}=\frac{|\alpha_0|^2}{|\alpha_{-1}|^2}=\frac{J_0^2(m)\cos(\alpha+\beta)}{J_1^2(m)\cos(\alpha-\beta)} \tag{7}$$

For a given α (or β), the OCSR is only dependent on β (or α), which means by tuning the polarization angle, α or β, the OCSR changes as well. In our case, we fix β=45°. To investigate the OCSR's tunability, Fig.2 plots the relationship between the OCSR and α. To obtain 0 dB OCSR, φ is predicted to around 42° at m=0.1. When m is increased from 0.1 to 0.2, 0.5, or 1, φ is supposed to adjust to 39°, 30°, or 15°(as inserted in Fig.2). Since minus OCSR is hardly used in practice, Fig.2 presents a near linear relationship between OCSR (>0 dB) and required polarization angle α. Thus the OCSR's tuning can be simply realized by adjusting the PC between CW laser and PolM. In practice, a smaller m is always preferable since small single modulation can reduce the power level in high order harmonic distortion. Besides, a smaller m will lead to lower third order inter-modulation distortion when SCM signals (N>1) is employed. In the following case, we use m=0.1.

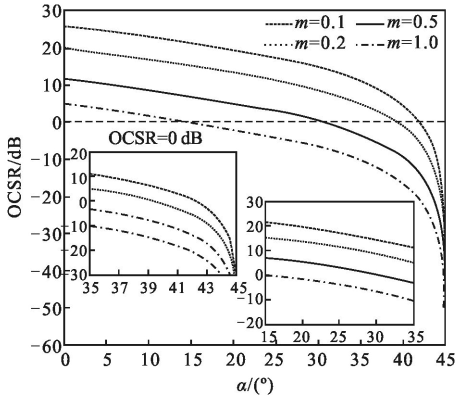

Fig.2 Calculated OCSR versus α at different m

For the case of multi-RF tone modulation(N>1), Eq.(8) gives us a simple expression of RF power after detection[7]:

$$P_{\rm RF}=2\mathscr{R}^2P_{\rm opt}^2\frac{\text{OCSR}}{(\text{OCSR}+N)^2} \tag{8}$$

where $P_{\rm opt}=P_0+P_1+\cdots+P_N$ denotes input optical power, N is the number of RF tones. Here, we keep $P_{\rm opt}$ as constant. It can be observed from the equation that P_{RF} can only find its maximum value at OCSR=10·$\log_{10}(N)$(in dB). The maximum value of P_{RF} under the same input optical power also represents the best receiver sensitivity in a RoF links, as has already been demonstrated in Ref.[8–9]. Thus by tuning the OCSR to the optimum value (OCSR=10·$\log_{10}(N)$), receiver sensitivity can be greatly improved.

2 Simulation

To investigate its mechanism, simulations are preformed via OptiSystem 10.0. The setup can be found in Fig.1. A CW laser works at a carrier wavelength of 1 550.04 nm and linewidth of 0.8 MHz. Then a PC is employed to align the inject polarization direction at the PolM, which is designed via a Matlab program and a programmable module based on the PolM′s working characteristic. The injected polarization angle is α. Here, SCM signals (N=2 for example) is used as the driving signals. The subcarrier frequencies of two RF tones are 20 and 22 GHz. As stated in the previous section, small signal modulation is applied (m=0.1). Then a PC and an LP are connected. By tuning the PC, the output polarization angle is fixed as β=45°. After the LP, a standard 50/100 GHz OI (C band on ITU from 1 529.55 to 1 561.42 nm) is utilized to remove one sideband from the ODSB signal. In our case, the optical wavelength has been properly adjusted (λ_0=1550 nm), to make sure the optical carrier is located at the left edge of the filter. The OI′s pass band can be considered as an optical filter. Its centre wavelength is 1 550.116 nm and bandwidth is 50 GHz. As a proof-of-concept verification, its top flatness and attenuation are both considered as negligibly small.

Figure 3 plots the transmission response of the OI, and the optical spectra before and after the OI. The rolloff (or edge slop) of the OI should be high enough to suppress one sideband from the ODSB signals. As shown in Fig.3, the sideband at the shorter wavelength can be fully suppressed. For example, in our case, the rolloff parameter of OI is more than 300 dB/nm. Therefore, after the OI filtering, the 20 GHz sideband is suppressed for at least 40 dB, which is sufficient to obtain OSSB signals at the output port. Technically, the limit on the RF frequency is highly determined by the pass band′s rolloff parameter. In our case, the rolloff parameter is more than 300 dB/nm, thus the RF frequency of wireless signals higher than 20 GHz can be utilized in this work.

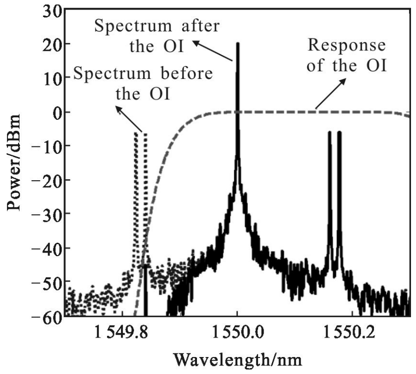

Fig.3 Simulated optical spectra before and after the 50/100 GHz OI, the transmission response of the OI

Then the output lightwave is amplified by a power controlled optical amplifier(PCOA) followed by a tunable optical filter (TOF) to filter the amplified spontaneous emission noise (ASE). The input optical power at the optical spectrum analyzer (OSA) and photodiode (PD) is maintained constant (P_{opt}=0 dB in Eq.(8) for example) by controlling the output optical power from the PCOA. The optical spectrum is then captured by the OSA. The results are shown in Fig.4 (inserted), which corresponding to OCSR =26, 21, 17.2, 11, 8, 0, −9 and −60 dB. To reach those values, polarization angle α is supposed to adjust to 0°, 15°, 25°, 35°, 38°, 42°, 44° and 45°, respectively. Note that the calculated(lines) and simulated(marks) results match closely. The OCSR′s tuning range can be easily found as −60–26 dB. Note that there is a shape falling of OCSR in Fig.4 when α is adjusted close to 45°. It may not be easy to realize and tune the minus OCSR in practice. However, since minus OCSR is hardly used in RoF link, that default will not affect the feasibility of this proposal.

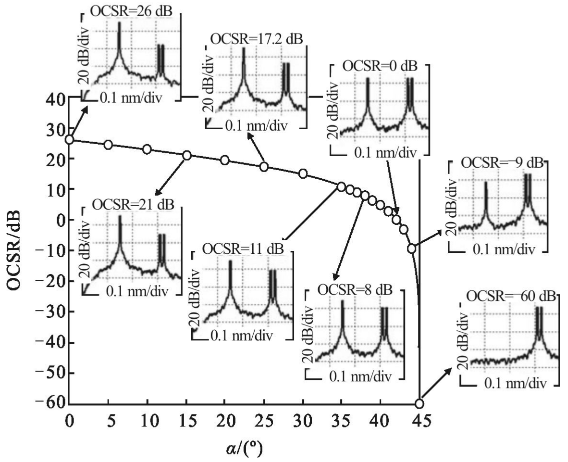

Fig.4 Calculated (lines) and simulated (marks) OCSR versus α, optical spectra are inserted

In our case, P_{opt}=0 dBm. An electrical spectrum analyzer(ESA) is used to capture the RF power level. Figure 5 shows the calculated(line), according to Eq.(8), and simulated(marks) normalized RF power versus the OCSR at different N. Note that −60 dB OCSR is not included mainly due to the impact of noise floor in optical spectrum (as shown in Fig.4 inserted). Except for that, the simulation results agree with the theory. Note that the peak RF power can only be found at 0 dB(N=1), 3 dB(N=2), 6 dB(N=4), or 9 dB(N=8). The optimum OCSR fits the relationship of OCSR = 10·$\log_{10}(N)$(in dB) very well. When considering data transmission, the bit error rate(BER) is proportional to the RF power, which means higher RF power will correspond to a better BER performance. Thus the best receiver sensitivity of a RoF link can be predicted by Fig.5, as has been demonstrated in Ref.[6−9].

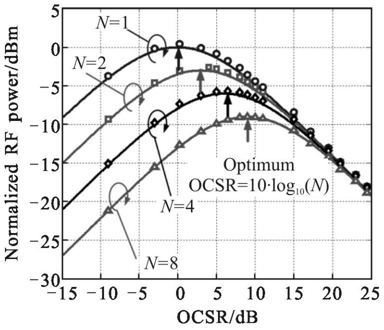

Fig.5 Calculated (lines) and simulated (marks) normalized RF power versus the OCSR at different N. The input optical power at PD is remained constant (P_{out}=0 dBm)

3 Conclusion

In summary, a RoF link based on polarization modulation has been analyzed by theory and verified by simulation. With careful adjustment of the polarization angle(α and β), a simplified expression of the OCSR in Eq.(7) can be obtained. At small signal modulation (m =0.1), the OCSR of the generated signals can be tuning form −60−26 dB. According to the analysis, the receiver sensitivity of RoF link can be improved by adjusting the OCSR to an optimum value (OCSR=10·$\log_{10}(N)$). This work also evaluates the tolerant range of bias-induced phase shift φ. It is found that φ should be controlled within a roughly range of 174°−186° for m=0.1. In practice, such a range can be done by using a commercially used bias voltage control circuit.

References:

[1] Li Tao, Rong Jian, Zhong Xiaochun. OFDM-ROF system simulation based on OptiSystem [J]. ***Infrared and Laser Engineering***, 2011, 40(6): 1154−1159. (in Chinese)

[2] Zhang Jianming, Lou Shuqin, Zeng Lulu. A scheme of full-duplex radio over fiber link model [J]. ***Infrared and Laser Engineering***, 2015, 44(5): 1599−1604. (in Chinese)

[3] Zhang Chan, Ning Tigang, Li Jing, et al. Single-sideband modulated radio-over-fiber system based on phase-shifted superstructure fiber Bragg grating [J]. ***Infrared and Laser Engineering***, 2016, 45(2): 0222001. (in Chinese)

[4] Graham H Smith, Dalma Novak, Zaheer Ahmed. Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators [J]. ***IEEE Transations on Microwave Theory and Techniques***, 1997, 45(8): 1410−1415

[5] Attygalle M, Lim C, Pendock G J, et al. Transmission improvement in fiber wireless links using fiber Bragg gratings [J]. ***IEEE Photonics Technology Letters***, 2005, 17 (1): 190−192.

[6] Li Jing, Ning Tigang, Pei Li, et al. An improved radio over fiber system with high sensitivity and reduced power

degradation by employing a triangular CFBG [J]. ***IEEE Photonics Technology Letters***, 2010, 22(7): 516-518.

[7] Li Jing, Ning Tigang, Pei Li, et al. Performance analysis of an optical single sideband modulation approach with tunable optical carrier-to-sideband ratio [J]. ***Optics & Laser Technology***, 2013, 48: 210-215.

[8] Xiao Shijun, Weiner A M. Optical carrier-suppressed single sideband(O-CS-SSB) Modulation using a hyperfine blocking filter based on a virtually imaged phased-array (VIPA)[J]. ***IEEE Photonics Technology Letters***, 2005, 17(7): 1522-1524.

[9] Bouchaib Hraimel, Zhang Xiupu, Pei Yinqing. Optical single-sideband modulation with tunable optical carrier to sideband ratio in radio over fiber systems [J]. ***Journal of Lightwave Technology***, 2011, 29(5): 775-781.