doi:10.3788/gzxb20144307.0706010

循环频移方法中射频信号的相位偏移对多载波稳定性及平坦度的影响

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摘　要:为了得到高性能的多载波光源，研究了射频信号中不同相位差对光多载波的影响. 通过理论分析可得，随着相位差从 90°降至 0°，光多载波性能会逐渐变差，但是相位差偏与 90°相差不大时，性能不会下降太多. 实验中通过移相器改变相位差，使相位差为 90°，45°，0°，得到循环前 IQ 调制器的输出光谱，并对比循环后光多载波性能. 实验结果显示，相位差为 90°时，循环前 IQ 调制器输出为较好的单边带光谱，循环后输出 50 条平坦稳定光多载波；相位差为 45°时，光多载波质量变差；相位差为 0°时，得不到光多载波. 因此，射频信号相位差为 90°时，光多载波的性能最佳，随着相位差变小，性能下降，但是相位差为 45°时，产生的光多载波仍可应用于光通信.

关键词:光通信；多载波；循环移频；相偏；稳定平坦

中图分类号:　　**文献标识码**:A　　**文章编号**:1004-4213(2014)07-0706010-5

Effects of RF Signal Phase Deviation on Generation of Stable and Flat Multi-carrier Based on Recirculating Frequency Shifter

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Abstract: In order to generate a high quality multi-carrier, the phenomenon caused by different phase deviation of radio frequency was analysed. In this paper, the theoretical analysis revealed that the quality of multi-carrier would deteriorate gradually when the phase deviation decreases from 90° to 0°. But when phase deviation is slightly different from 90°, the quality of multi-carrier is good enough for the application of optical communication. In the experiment, the qualities of multi-carriers with phase deviation of 90°, 45° and 0° were compared. The best performance is obtained at 90°. Under the 45° phase deviation, fifty carriers can also be otainted, but the quality decreases slightly that is good enough to apply to optical communication. And a multi-carrier under 0° phase deviation cannot be obtained.

Key words: Optical communication; Multi-carrier; RFS; Phase deviation; Stability and flatness

OCIS Codes: 060.0060; 140.0140; 230.0230

0 Introduction

The demand for bandwidth is increasing with more and more video streaming and proliferation of cloud computing, social media, and mobile data delivery[1-3]. There are three main ways to increase channel capacity when Polarization-Division Multiplexing (PDM) and coherent detection applied: 1) Electrical Time Division

Foundation item: The National Natural Science Foundation of China (Nos. 61271192, 60932004) and the National Hi-Tech R&D Program of China (No. 2013AA013401)

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Received: Oct. 22, 2013; **Accepted**: Dec. 10, 2013

http://www.photon.ac.cn

Multiplexing (ETDM); 2) adoptling higher-level Quadrature Amplitude Modulation (QAM) formats for increasing the spectral efficiency; 3) employing multiple optical carriers (super channels), which can overcome bandwidth limitations of optoelectronic components[4].

Among different multicarrier technologies, Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) and Nyquist Wavelength Division Multiplexing (Nyquist WDM) have shown greatest potential for higher Spectral Efficiency (SE)[5-6].

There are many methods to generate optical multi-carrier. Mostly, a cascaded Mach-Zehnder modulator and Phase Modulator (PM), a cascaded polarization modulator and PM can′t obtain stability and a large number of multi-carriers without high Radio Frequency (RF) amplifier[7-8]. Additionally, a flat multi-carrier can be generated by a Mode Locked Laser (MLL), but this method can not conveniently tune the frequency spacing of multi-carrier[9-10].

One popular approach is Recirculating Frequency Shifting (RFS) for generating multi-carrier in CO-OFDM and Nyquist WDM, which can generate high quality multi-carrier and the frequency spacing can tune by the RF signal[11-12]. In the multi-carrier transmission system, the flatness and stability of the generated multiple optical carriers is a critical point which directly affect overall performance. In order to gain the high-quality multi-carrier for optical communication, we should give a detailed analysis.

In this paper, we theoretically and experimentally analyze the influences result from the non-ideal phase deviation of RF-drive signals in detail. According to analysis, a flat and stable 50 multi-carrier has been experimentally implemented through RFS. Meanwhile, practical experimental results fit well with theoretical analysis.

1 Theoretical analysis of the impact factors

Fig. 1 depicts experimental setup of RFS structure which is generally discussed in[13-17], It consists of a Tunable Laser Source (TLS), a closed fiber loop, which includes I/Q modulator, Optical Amplifier (OA) with high gain for compensating the modulation loss, a tunable optical band-pass-filter with suitable central wavelength and flat-top shape to select the desire number of carriers, two Polarization Controllers (PC), a 50:50 coupler. The I/Q modulator can be considered contains two Mach-Zehnder intensity modulators placed parallel in two arms. Ideally, the input optical signal is $E_{\text{in}}(t)=A\exp(\mathrm{j}\pi f_0 t)$, and the two RF drive signals of the I/Q modulator are $f_{\text{I}}(t)=V_{\text{pp}}\sin(2\pi f_{\text{s}}t)$, $f_{\text{Q}}=V_{\text{pp}}\cos(2\pi f_{\text{s}}t)$, respectively. But in practical condition, the phase and amplitude of In-Phase branch are not identical with the Quadrature branch, which may bring serious influence on flatness of generated multi-carrier.

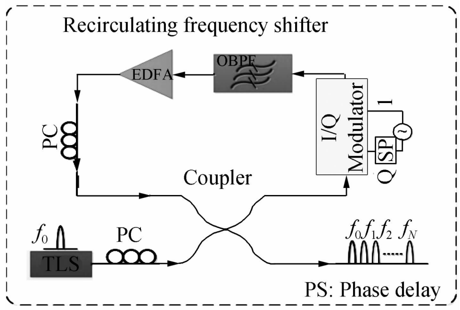

Fig. 1 The schematic of RFS

Assuming the RF signals fed into I/Q modulator are $f_{\text{I}}(t)=V_{\text{pp}}\sin(2\pi f_{\text{s}}t)$, $f_{\text{Q}}=V_{\text{pp}}\sin(2\pi f_{\text{s}}t+\theta)$ and the total number of desired optical carriers is $N+1$, with the frequency: f_0, f_1, $\cdots f_N$, respectively. The output electronic field of I/Q modulator is

$$E_{\text{out}}(t)=E_{\text{in}}(t)/2[\mathrm{j}\sin(\pi f_{\text{I}}(t)/2V_{\pi})+\sin(\pi f_{\text{Q}}(t)/2V_{\pi})] \tag{1}$$

with the Jacobi-Anger expansion, Eq. (1) can be written as

$$E_{\text{out}}=E_{\text{in}}(t)/2[\mathrm{j}\sin(\delta_m\sin(2\pi f_{\text{s}}t))+\sin(\delta_m\cdot\sin(2\pi f_{\text{s}}t+\theta))]=E_{\text{in}}(t)\sum_{k=1}^{\infty}\{\mathrm{J}_{2k-1}(\delta_m)\cdot\{\mathrm{j}\sin[2\pi(2k-1)f_{\text{s}}t]+\sin[2\pi(2k-1)\cdot(f_{\text{s}}t+\theta)]\}\} \tag{2}$$

where the $\mathrm{J}_n(\delta_m)$ is the nth order Bessel function with $\delta_m=\pi V_{\text{pp}}/2V_{\pi}$.

Eq. (3) is substituted by $\mathrm{J}_n=\mathrm{J}_n(\delta_m)$, $\theta_k=k*\theta/2-\pi/4$, $f_k=2\pi k f_{\text{s}}t$, $\varphi_k=f_k+\theta_k$, $C_k=\cos\theta_k$, $S_k=\sin\theta_k$, Empirically, the phase modulation depth δ_m is near one.

$$E_{\text{out}}(t)=\frac{E_{\text{in}}(t)}{2}\sum_{k=1}^{\infty}\mathrm{J}_{2k-1}[\mathrm{e}^{\mathrm{j}f_{2k-1}}+\mathrm{e}^{\mathrm{j}(f_{2k-1}+2\theta_{2k-1})}-\mathrm{e}^{-\mathrm{j}(f_{2k-1}+2\theta_{2k-1})}-\mathrm{e}^{-\mathrm{j}f_{2k-1}}]=E_{\text{in}}(t)\sum_{k=1}^{\infty}\mathrm{J}_{2k-1}\{\mathrm{e}^{\mathrm{j}(f_{2k-1}+\theta_{2k-1})}\cos(\theta_{2k-1})-\mathrm{j}\mathrm{e}^{-\mathrm{j}(f_{2k-1}+\theta_{2k-1})}\sin(\theta_{2k-1})\}=E_{\text{in}}(t)\sum_{k=1}^{\infty}\mathrm{J}_{2k-1}(C_{2k-1}\mathrm{e}^{\mathrm{j}\varphi_{2k-1}}-\mathrm{j}S_{2k-1}\mathrm{e}^{-\mathrm{j}\varphi_{2k-1}}) \tag{3}$$

According to the features of Bessel function, $\mathrm{J}_3(\delta_m)$ is the dominant among all the harmonics, and we can ignore all the other high order harmonics beyond third order. So the transfer function of I/Q modulator can be expressed as

$$T_0=\frac{E_{\text{out}}(t)}{E_{\text{in}}(t)}=\mathrm{J}_1(C_1\mathrm{e}^{\mathrm{j}\varphi_1}-\mathrm{j}S_1\mathrm{e}^{-\mathrm{j}\varphi_1})+\mathrm{J}_3(C_3\mathrm{e}^{\mathrm{j}\varphi_3}-\mathrm{j}S_3\mathrm{e}^{-\mathrm{j}\varphi_3})=\mathrm{J}_1[(C_1\mathrm{e}^{\mathrm{j}\varphi_1}-\mathrm{j}S_1\mathrm{e}^{-\mathrm{j}\varphi_1})+b(C_3\mathrm{e}^{\mathrm{j}\varphi_3}-\mathrm{j}S_3\mathrm{e}^{-\mathrm{j}\varphi_3})] \tag{4}$$

where $b=\mathrm{J}_3/\mathrm{J}_1$ is the crosstalk coefficient which is function of the I/Q modulator drive voltage. Obviously, the gain of OA in the ideal case can be regarded as $G_{oa}=1/J_1^2$ for compensating the loss of the I/Q modulator. The transfer function can be simplified as

$$T=(C_1 e^{j\varphi_1}-jS_1 e^{-j\varphi_1})+b(C_3 e^{j\varphi_3}-jS_3 e^{-j\varphi_3}) \quad (5)$$

Under the less crosstalk condition $|b|\ll 1$

$$T^n=[(C_1 e^{j\varphi_1}-jS_1 e^{-j\varphi_1})+b(C_3 e^{j\varphi_3}-jS_3 e^{-j\varphi_3})]^n\approx [(C_1 e^{j\varphi_1}-jS_1 e^{-j\varphi_1})^n+nb(C_1 e^{j\varphi_1}-jS_1 e^{-j\varphi_1})^{n-1}(C_3 e^{j\varphi_3}-jS_3 e^{-j\varphi_3})] \quad (6)$$

If θ is closed to $\pi/2$, $S_1\ll C_1$, $C_3\ll S_3$ and $S_1\ll 1$, $C_3\ll 1$. We can ignore the product of two number which is much smaller than 1.

$$(C_1 e^{j\varphi_1}-jS_1 e^{-j\varphi_1})^n\approx C_1^n e^{jn\varphi_1}-jnC_1^{n-1}S_1 e^{j(n-2)\varphi_1} \quad (7)$$

$$n(bC_1 e^{j\varphi_1}-jbS_1 e^{-j\varphi_1})^{n-1}(C_3 e^{j\varphi_3}\text{-}jS_3 e^{-j\varphi_3})\approx -jnbC_1^{n-1}S_3 e^{j[(n-1)\varphi_1-\varphi_3]} \quad (8)$$

$$T^n\approx C_1^n e^{jn\varphi_1}-jnC_1^{n-1}S_1 e^{j(n-2)\varphi_1}-jnbC_1^{n-1}\cdot S_3 e^{j[(n-1)\varphi_1-\varphi_3]} \quad (9)$$

The output which has experienced N round trips is shown as

$$E_{Nout}(t)=E_{in}(t)\sum_{n=0}^{N}T^n\approx E_{in}(t)\cdot\sum_{n=0}^{N}\{C_1^n e^{jn\varphi_1}-jnC_1^{n-1}S_1 e^{j(n-2)\varphi_1}-jnbC_1^{n-1}S_3 e^{j[(n-1)\varphi_1-\varphi_3]}\} \quad (10)$$

In Eq. (10), the term $\sum_{n=0}^{N}C_1^n e^{jn\varphi_1}$ corresponds to the required frequency components at $(0, f_s, 2f_s \cdots Nf_s)$, which is signal component.

$\sum_{n=0}^{N}-jnC_1^{n-1}S_1 e^{j(n-2)\varphi_1}$ and $\sum_{n=0}^{N}-jnbC_1^{n-1}S_3\cdot e^{j[(n-1)\varphi_1-\varphi_3]}$ is unwanted crosstalk component. The crosstalk frequencies are located at $-2f_s, -f_s, 0\cdots(N-2)f_s$ and $-4f_s, -3f_s, -2f_s\cdots(N-4)f_s$, respectively.

If θ is equal to $\pi/2$, $\sum_{n=0}^{N}-jnbC_1^{n-1}S_3 e^{j[(n-1)\varphi_1-\varphi_3]}$ becomes the only crosstalk component. But when θ is slightly deviated from $\pi/2$, $\sum_{n=0}^{N}-jnC_1^{n-1}S_1 e^{j(n-2)\varphi_1}$ and $\sum_{n=0}^{N}-jnbC_1^{n-1}S_3 e^{j[(n-1)\varphi_1-\varphi_3]}$ are jointly impact the performance of multi-carrier. However, the crosstalk component is much smaller than $\sum_{n=0}^{N}C_1^n e^{jn\varphi_1}$, so the quality of the multi-carrier is sufficient for the application of optical communication.

2 The experiment setup and result

In order to match the flat gain range of OA, the operating wavelength of TLS is set at 1 560.1 nm, with power of 10 dBm. The I/Q modulator is driven by two 12.5 GHz RF signal with same amplitude and $\pi/2$ phase deviation for generating a Single Side Band(SSB) modulation as a seed signal. The bandwidth of optical band-pass filter is set to 5 nm. The output of EDFA is fixed at 27 dBm for compensating the power consumption of loop, including insertion loss of I/Q modulation and filter. In order to obtain enough power of RF, we adopted two microwave power amplifiers to amplify the amplitude of RF drive signals of I/Q ports, respectively.

First of all, according to the above settings, obtain a best transfer function of SSB modulation by adjusting the bias voltage of I/Q modulator as depicted in Fig. 2. Under the appropriate adjust of DC bias voltage and polarization, a flat and stable 50 multi-carriers with 12.5 GHz-spaced, of which the total bandwidth is 5nm, is realized as shown in Fig. 3.

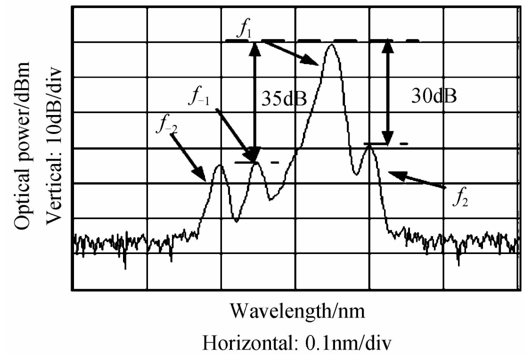

Fig. 2 The optical spectrum output of I/Q modulator under RF signal with $\pi/2$ phase deviation

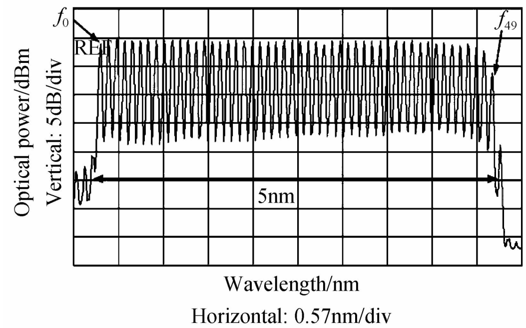

Fig. 3 The 50 multi-carriers under RF signal with $\pi/2$ phase deviation

When the I/Q modulator s driven by RF signals with $\pi/4$ phase deviation, the transfer function output is shown in the Fig. 4. The impact caused by f_{-1} is more serious than the balanced operation condition. As shown in Fig. 5, the flatness of multi-carrier goes worse than which in Fig. 3, obviously. But the multi-carrier is enough to apply to optical communication[7, 10-11].

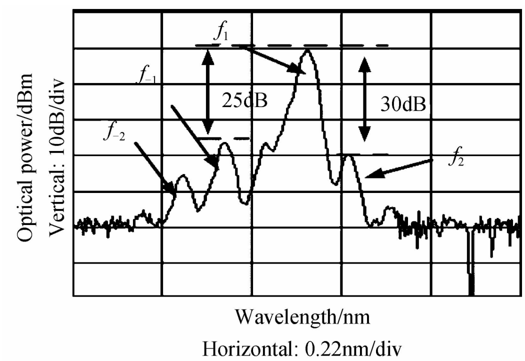

Fig. 4 The optical spectrum output of I/Q modulator under RF signal with $\pi/4$ phase deviation

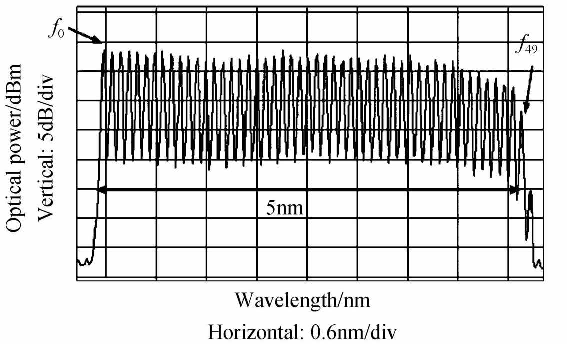

Fig. 5 The 50 multi-carriers under RF signal with π/4 phase deviation

When the I/Q modulator is driven by RF signals without phase deviation, the function output is depicted in the Fig. 6. The range of f_{-1} keeps pace with f_1. It can be explained by Eq. (5). As shown in chapter 1, the output of RFS is worsen when the two RF signals with same phase. The experiment result shown in Fig. 7 coincides with the theoretical analysis.

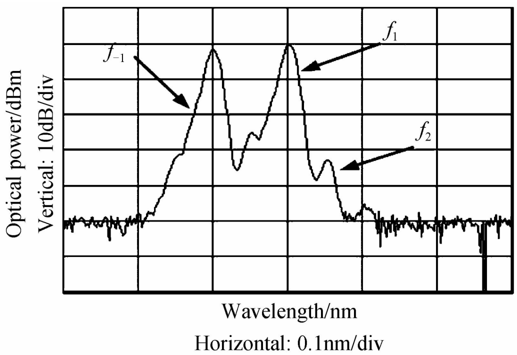

Fig. 6 The optical spectrum output of I/Q modulator under RF without phase deviation

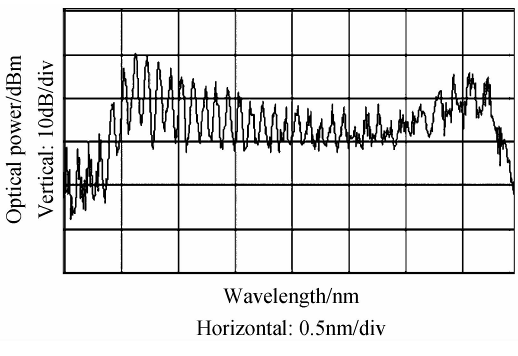

Fig. 7 The 50 multi-carriers under RF signal without phase deviation

3 Conclusions

In this paper, we analytically and experimentally optimize the multi-carrier. 12. 5GHz-spaced multi-carriers with high flatness and stability have been successfully generated by adopted RFS method. Theoretical analysis has been demonstrated to reveal the critical points which are closely related with the flatness and stability of multi-carrier, such as the range phase deviation between the I and Q signals. The phase deviation of RF signals for generation of multi-carrier based on RFS is not necessary to precisely fit π/2. Experiment has been implemented to verify the theoretical analysis. The experiment researches will be available approach for the Tbps multi-carrier transmission in optical communication.

References

[1] SWANSON B, GILDER G. Estimating the exaflood-the impact of video and rich media on the internet-a 'zettabyte' by 2015[J]. *Discovery Institute*, Jan, 2008, 29.

[2] TKACH R W. Scaling optical communications for the next decade and beyond[J]. *Bell Labs Technical Journal*, 2010, **14**(4): 3-9.

[3] ESSIAMBRE R, TKACH R W. Capacity trends and limits of optical communication networks[C]. Proceedings of the IEEE, 2012, **100**(5): 1035-1055.

[4] JIA Z, YU J, CHIEN H C, *et al*. Field transmission of 100 G and beyond: multiple baud rates and mixed line rates using nyquist-WDM technology [J]. *Journal of Lightwave Technology*, 2012, **30**(24): 3793-3804.

[5] ZHU B, LIU X, CHANDRASEKHAR S, *et al*. Ultra-long-haul transmission of 1. 2-Tb/s multicarrier no-guard-interval CO-OFDM superchannel using ultra-large-area fiber [J]. *Photonics Technology Letters*, *IEEE*, 2010, **22**(11): 826-828.

[6] SANO A, YAMADA E, MASUDA H, *et al*. No-guard-interval coherent optical OFDM for 100-Gb/s long-haul WDM transmission[J]. *Journal of Lightwave Technology*, 2009, **27**(16): 3705-3713.

[7] ZHANG L, SONG Y, ZOU S, *et al*. Flat frequency comb generation based on Mach-Zehnder modulator and phase modulator[C]. Communication Technology (ICCT), 2010 12th IEEE International Conference on. IEEE, 2010: 211-213.

[8] CHEN C, HE C, ZHU D, *et al*. Generation of a flat optical frequency comb based on a cascaded polarization modulator and phase modulator[J]. *Optics letters*, 2013, **38**(16): 3137-3139.

[9] HILLERKUSS D, SCHMOGROW R, MEYER M, *et al*. Single-laser 32. 5 Tbit/s nyquist WDM transmission [J]. *IEEE/OSA Journal of Optical Communications and Networking*, 2012, **4**(10): 715-723.

[10] KONG Yong, LU Yutian, WANG Ning. Influence of gain medium's dispersion on pulse width and chirpof mode-locked laser [J]. *Acta Photonica Sinica*, 2003, **32**(9): 1035-1037.

[11] MA Y, YANG Q, TANG Y, *et al*. 1-Tb/s per channel coherent optical OFDM transmission with subwavelength bandwidth access [C]. Optical Fiber Communication Conference, Optical Society of America, 2009.

[12] MA Y, YANG Q, TANG Y, *et al*. 1-Tb/s single-channel coherent optical OFDM transmission with orthogonal-band multiplexing and subwavelength bandwidth access [J]. *Journal of Lightwave Technology*,, 2010, **28**(4): 308-315.

[13] TIAN F, ZHANG X, LI J, *et al*. Generation of 50 stable frequency-locked optical carriers for Tb/s multicarrier optical transmission using a recirculating frequency shifter [J]. *Journal of Lightwave Technology*, 2011, **29**(8): 1085-1091.

[14] LI J, LI X, ZHANG X, *et al*. Analysis of the stability of recirculating frequency shifter used as a multi-tone wideband

light source for Tb/s multi-carrier optical transmission[C]. Optical Communication (ECOC), 2010 36th European Conference and Exhibition on IEEE, 2010: 1-3.

[15] LI J, ZHANG X, TIAN F, *et al*. Generation of stable and high-quality multicarrier source based on re-circulating frequency shifter for Tb/s optical transmission[C]. Optical Fiber Communication Conference. Optical Society of America, 2011.

[16] LI J, LI X, ZHANG X, *et al*. Analysis of the stability and optimizing operation of the single-side-band modulator based on re-circulating frequency shifter used for the T-bit/s optical communication transmission[J]. *Optics Express*, 2010, **18**(17): 17597-17609.

[17] LI J, ZHANG X, TIAN F, *et al*. Theoretical and experimental study on generation of stable and high-quality multi-carrier source based on re-circulating frequency shifter used for Tb/s optical transmission[J]. *Optics express*, 2011, **19**(2): 848-860.