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An RoF system with continuously tunable optical carrier-to-sideband ratio based on polarization multiplexing*

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In order to improve radio over fiber (RoF) system performance and reduce system complexity, a novel RoF system scheme with continuously tunable optical carrier-to-sideband ratio (*OCSR*) was proposed. Using polarization multiplexing technology, the *OCSR* can be tuned from –36 dB to 26 dB by adjusting a polarization controller (PC). The effects of polarization angle of PC, modulation index and extinction ratio on *OCSR* were studied by theoretical analysis and experimental simulation, in which the results of theoretical calculation and experimental simulation are in good agreement. It is found that the receiver sensitivity can be improved 7.8 dB by tuning the *OCSR* from 10.41 dB to 0 dB. The power penalty is 0.07 dB for the 0 dB *OCSR* after 40 km transmission, which means the impact from the fiber link can be ignored.

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Radio over fiber (RoF), integration of optical and wireless system, has been considered as a promising technology in the future broadband wireless communication[1-3]. There are many modulation schemes to realize the modulation of mm-wave signal to light wave in RoF system, such as optical double sideband (ODS) modulation, optical carrier suppressed double sideband (OCS-DS) modulation and optical single sideband (OSSB) modulation[4-6]. Compared with the other two modulation schemes, the OSSB can reduce the power fading and improve the spectral efficiency, which is considered as the most promising modulation scheme. Recent research also find that the receiver sensitivity can be significantly improved by tuning the optical carrier-to-sideband ratio (*OCSR*), and the optimum *OCSR* varies with the number of RF tones according to $OCSR=10\log_{10}(N)$ in sub-carrier multiplication (SCM) RoF system (N is the number of RF tones). Thus, how to realize tunable *OCSR* is becoming more and more important.

Numerous efforts have been devoted to implementing the OSSB with tunable *OCSR*. To decrease the *OCSR* and improve the receiver sensitivity, fiber Bragg grating (FBG) was used to suppress one sideband of the ODS or part optical carrier of the OSSB[7,8]. Stimulated Brillouin scattering (SBS) was used to tune the *OCSR* in Ref.[9], but this method would increase the second-order harmonic distortion. The OSSB can also be generated by dual-parallel MZM[10]. Firstly, an optical filter is used to remove one sideband to achieve the OSSB modulation, then the *OCSR* was continuously tuned by changing the direct current (DC) bias voltages of the dual-parallel MZM. Polarization modulator (PolMs) or cascaded PolMs could also be used to achieve the tunable *OCSR*[11,12]. However, in these schemes, optical filter would make the OSSB modulation wavelength dependent and reduce tunable range, the dual-parallel MZM would require complex DC bias voltages controlling, and the cascaded PolMs usually needs complex phase controlling, which cause the limited bandwidth and complicated structure.

In this paper, a novel RoF system scheme with continuously tunable *OCSR* is proposed and analyzed, using polarization multiplexing technology and polarization controller (PC) to adjust *OCSR*.

Fig.1 shows the schematic diagram of the proposed OSSB system with tunable *OCSR*. The transmitting end consists of a laser diode (LD), a polarization controller (PC), a polarization beam splitter (PBS), an MZM modulator, a polarization beam combiner (PBC) and a polarizer (Pol). The Solid line denotes light path and dotted line denotes circuit path. The continuous light emitted from the LD can be expressed as $E_c(t)=E_c\exp(j\omega_c t)$, where E_c is the amplitude of light and ω_c is the angular frequency of light. The PBS splits the light emitted from LD into two orthogonal polarization directions (i.e., X

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pol and *Y* pol). Assuming the incident light is oriented at an angle of ϕ to one principal axis of PBS controlled by PC. *X* pol light is feed into the MZM driven by RF signal $E_{rf}(t)=E_{rf}\exp(j\omega_{rf}t)$, where E_{rf} and ω_{rf} are the RF signal amplitude and angular frequency. The MZM are operated at quadrature point (Bias *a*=0, Bias $b=V_\pi/2$, V_π denotes the half-wave voltage of MZM). Under small signal modulation, the output optical field of MZM in *X* pol can be expressed as

$$E_{x\mathrm{MZM}}(t)=\frac{E_\mathrm{c}}{10^{(IL/20)}}[(1-\gamma+\mathrm{j}\gamma)J_0(m)\mathrm{e}^{\mathrm{j}\omega_\mathrm{c}t}-\mathrm{j}J_{-1}(m)\mathrm{e}^{\mathrm{j}(\omega_\mathrm{c}+\omega_\mathrm{rf})t}]\cos(\phi)\ , \tag{1}$$

where *IL* is insertion loss, γ denotes the power splitting ratio of MZM, $m=\pi E_{rf}/V_\pi$ is modulation index, and $J_n(m)$ denotes the Bessel function of first kind of order *n*. The relation between γ and extinction ratio *ER* is $\gamma=0.5(10^{ER/20}-1)/10^{ER/20}$.

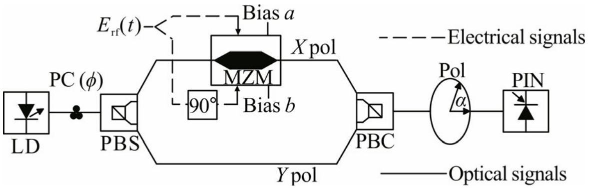

Fig.1 Schematic diagram of the proposed OSSB system with tunable *OCSR*

The optical field in *Y* pol can be expressed as

$$E_y(t)=E_\mathrm{c}\mathrm{e}^{\mathrm{j}\omega_\mathrm{c}t}\sin(\phi)\ . \tag{2}$$

Then the PBC combine the two orthogonal polarized signals $E_{x\mathrm{MZM}}$ and E_y. Finally, in order to simplify the analysis, the Pol with its principle polarization direction α=45° relative to one principal axis of PBC is employed. The output optical field of Pol can be expressed as

$$E_\mathrm{pol}(t)=E_{x\mathrm{MZM}}(t)\cos(\pi/4)+E_y(t)\sin(\pi/4)=\frac{\sqrt{2}}{2}[\frac{E_\mathrm{c}}{10^{(IL/20)}}(1-\gamma+\mathrm{j}\gamma)J_0(m)\cos(\phi)+E_\mathrm{c}\sin(\phi)]\mathrm{e}^{\mathrm{j}\omega_\mathrm{c}t}-\frac{\sqrt{2}}{2}\frac{E_\mathrm{c}}{10^{(IL/20)}}\mathrm{j}J_{-1}(m)\cos(\phi)\mathrm{e}^{\mathrm{j}(\omega_\mathrm{c}+\omega_\mathrm{rf})t}\ . \tag{3}$$

As can be seen from Eq.(3), the *OCSR* is

$$R_{OCS}=20\log_{10}\frac{\left|10^{-IL/20}(1-\gamma+\mathrm{j}\gamma)J_0(m)\cos(\phi)+\sin(\phi)\right|}{\left|10^{-IL/20}J_{-1}(m)\cos(\phi)\right|}\ . \tag{4}$$

Eq.(4) shows that *OCSR* R_{OCS} is a function of modulation index *m* , extinction ratio *ER* and PC's ϕ to one principal axis of PBS. At the receiving end, the PIN photodiode receives optical signal and converts it into an electrical signal.

For a given value of *ER*=100 dB (ideal case), the *OCSR* R_{OCS} is dependent on *m* and ϕ. To investigate the *OCSR* tunability, Fig.2 plots the curves between the calculated R_{OCS} and ϕ at different *m* (The change of *m* is realized by changing the amplitude of RF driving signal). The *OCSR* can be theoretically changed from 29.3 dB to –22.3 dB at *m*=0.1; while for *m*=0.157, the *OCSR* can be varied from 26 dB to –36 dB, which is the widest tuning range among these curves in Fig.2. Fig.2 also shows that the minimum R_{OCS} varies with *m*, the reason is that R_{OCS} is also the function of *m*. To obtain 0 dB *OCSR* (R_{OCS}=0 dB is the optimum *OCSR* for one subcarrier modulation according to $OCSR=10\log_{10}(N)$), ϕ is around –23.1°at *m*=0.1, as shown in Fig.2. When *m* is increased from 0.1 to 0.157, 0.5, 1 or 1.5, ϕ should be adjusted to –23.8°, –27°, –29° and –27.4°. Small modulation index *m* could reduce the high order sidebands and improve radio frequency spurious suppression-ratio (*RFSSR*). Thus, in the following cases, we chose small modulation index *m*=0.157.

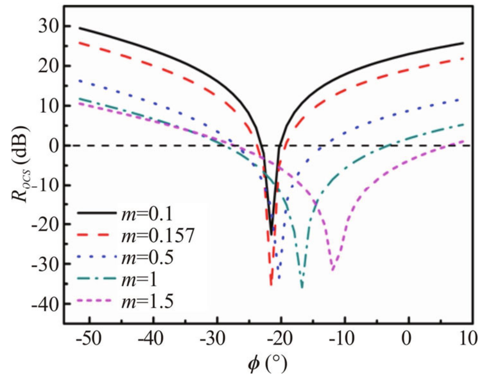

Fig.2 The calculated R_{OCS} versus ϕ at different *m*

Fig.3 shows the relationship between calculated R_{OCS} and *ER*. As can been see, R_{OCS} decreases linearly from 19 to 0.2 dB with the increase of *ER* from 0 dB to 30 dB, and R_{OCS} keeps 0 dB as the *ER* is greater than 30 dB. Thus, in the following cases, the *ER* is assumed to be 30 dB.

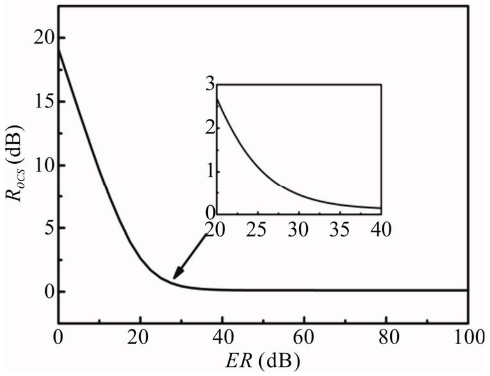

Fig.3 The calculated R_{OCS} versus *ER*

To verify the theory mentioned above, unmodulated system experimental simulations are performed according to Fig.1 via OptiSystem. An optical signal from the LD with frequency of 193.1 THz and linewidth of 10 MHz is sent to PC which connects the LD and PBS. 40 GHz RF signal is split into two paths with 90° out of phase to drive the MZM. V_π of MZM biased at quadrature point is 4 V.

For the sake of comparison with theoretical results, through setting V_{rf}=0.2 V, the modulation index m can be calculated as 0.157, and the high orders sidebands are ignored in this case.

Fig.4 shows the relationship between R_{OCS} and ϕ. As shown in Fig.4, the line denotes calculation results, and the marks denote experimental simulation results. The inserts in Fig.4 are optical spectrums with R_{OCS}=20.4, 0 and –20.24 dB, which are corresponding to ϕ=–40°, –23.74° and –22.11°, respectively. In fact, the two results coincide with each other, indicating that the experimental simulation and theoretical calculation are relatively consistent.

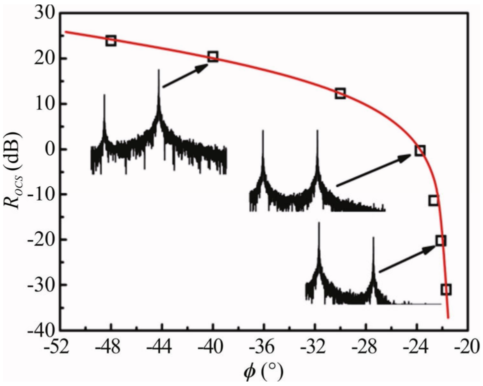

Fig.4 The calculated (line) and the simulated (mark) R_{OCS} versus ϕ

In the experimental simulation, transmitter power is maintained at 0 dBm, and the relationship between the RF power and R_{OCS} is shown in Fig.5. It is pretty obvious that the RF power has the maximum value at R_{OCS}=0 dB. According to signal theory, bit error rate (*BER*) is closely related to RF power. In other words, the *BER* at R_{OCS}=0 dB is the lowest among these cases. The 40 GHz RF spectrum at R_{OCS}=0 dB is given in the form of insert, as shown in Fig.5.

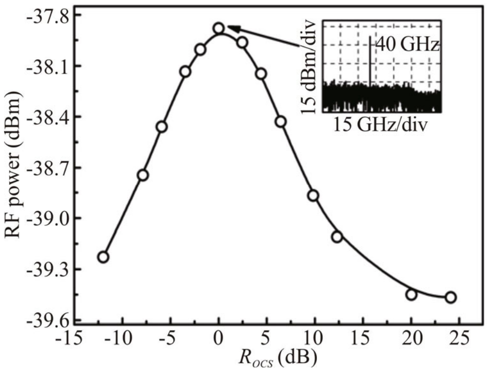

Fig.5 The RF power versus R_{OCS}

To evaluate transmission capacity and system performance, the modulated system experimental simulation is carried out as shown in Fig.6. 3 Gbit/s downlink data with word length of 2^{31}–1 is carried by the 40 GHz RF signal through a mixer to drive the MZM in X pol. By adjusting the ϕ of PC, the output modulated signal is kept at 0 dB R_{OCS}. At the receiving end, the signal detected by PIN after standard single mode fiber (SSMF) is demodulated by self homodyne technique, by which the local oscillator (LO) can be saved and system complexity and cost can be reduced. A low pass filter (LPF) with a bandwidth of 2.25 GHz is used to filter the out-of-band noise. The Q value, *BER*, eye diagram and other parameters are obtained by the *BER* tester (BERT).

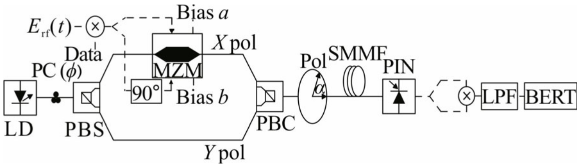

Fig.6 Schematic diagram of downlink RoF system

The relationship between Q value and transmission distance is analyzed as shown in Fig.7. When the transmission distance is less than 15 km, the Q values increase with the transmission distance increasing, which may result from the advantages of OSSB, including low power fading and high spectral efficiency mentioned above. When the transmission distance exceeds 15 km, the Q value linearly decreases, which indicates that the effect of cumulative dispersion and loss in the fiber link linearly increase. As can be seen, the transmission distances are 74.6 km, 63.1 km and 41.4 km at Q=6 (corresponding to BER=10^{-9}) for R_{OCS}=0, 5.64 dB and 10.41 dB, respectively. The inserts are eye diagrams for different R_{OCS} after 40 km transmission, which verify that the system performance is the best at R_{OCS}=0 dB.

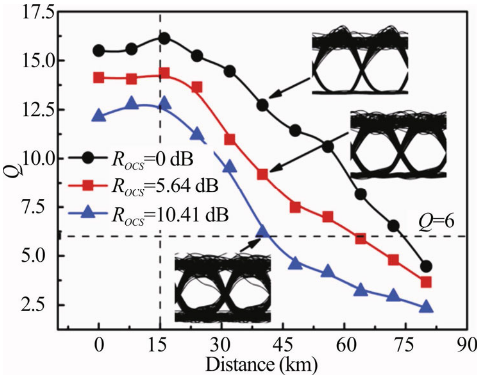

Fig.7 Q value versus distance at different R_{OCS}

Fig.8 shows the *BER* curves versus downlink received power at different distances and R_{OCS}. In the case of BTB, the receiver sensitivities at BER=10^{-9} are –41, –38.2 dBm and –33.2 dBm for R_{OCS}=0, 5.64 dB and 10.41 dB, respectively. It means that the receiver sensitivity can be improved 7.8 dB by tuning R_{OCS} from 10.41 dB to 0 dB. After 40 km transmission, the receiver sensitivities at BER=10^{-9} are –40.93 dBm, –36.41 dBm and –28.9 dBm for R_{OCS}=0, 5.64 dB and 10.41 dB, respectively. Compared

–41dB receiver sensitivity at BTB and R_{OCS}=0 dB with –28.9 dB receiver sensitivity at 40 km transmission and R_{OCS}=10.41 dB, it is degraded 12.03 dB, in which 7.8 dB is caused by the incompatible R_{OCS} and 4.23 dB is caused by dispersion and fiber loss. It also can be found that, after 40 km transmission, the power penalties are 0.07 dB, 1.79 dB and 4.3 dB at $BER=10^{-9}$ for R_{OCS}=0, 5.64 dB and 10.41 dB, respectively. That means the impact from the link can be ignored for R_{OCS}=0 dB after 40 km transmission.

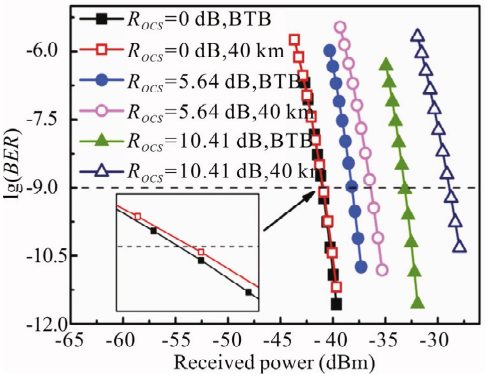

Fig.8 *BER* curves versus received power for downlink at different distances and R_{OCS}

In summary, based on polarization multiplexing technology, a novel RoF system scheme with continuously tunable *OCSR* is proposed and demonstrated. The *OCSR* can be tuned form –36 dB to 26 dB by adjusting the ϕ of PC from –51.5° to –21.5° at m=0.157 and ER=30 dB. It is found that the receiver sensitivity can be improved 7.8 dB by tuning the *OCSR* from 10.41 dB to 0 dB. After 40 km transmission, the power penalty is 0.07 dB for R_{OCS}=0 dB, which means the impact from the fiber link can be ignored. Wavelength dependent devices and complex modulators are not used in the proposed scheme, which is simple in structure, easy to tune the *OCSR*, reliable in performance, and can provide a strong reference for the actual design of ROF system.

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