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Millimeter-wave multi-carrier generation for WDM-ROF system without ultra-high-speed modulator

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We propose a novel method of multi-carriers generation for wavelength-division-multiplexed millimeter-wave-band radio-on-fiber system, and define carrier-to-carrier rate (CCR) to evaluate the scheme performance. Firstly, we experimentally generated a super-continuum source (SCS) with 20-dB width of more than 260 nm around 1550 nm by coupling a femto-second pulses lauched by the semiconductor mode-locked laser into two passages of 5-m-long high nonlinear photonic crystal fibers (PCFs) with opposite dispersion value. Secondly, we used a sampled fiber Bragg grating (SFBG) to filter spectrum, and the results showed that spectrum was sliced into 20 channels with -0.3-0.3 dB Peak fluctuation. Moreover, each two adjacent channels can be filtered out as one of radio-frequency carriers, and the amplitude differences of two sub-carriers in wavelength-division-multiplexed millimeter-wave-band radio-on-fiber system are tiny to ensure optimal CCR.

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1. Introduction

The wavelength division multiplexing (WDM) technology is an indispensable link for millimeter wave band ROF system since it can support the fluent information interaction between numerous base stations and central station. The WDM-ROF system which uses huge capacity of single fiber channel can meet the increasing requirement of bandwidth for wideband wireless communication services, simplify architecture of base station and maintenance process, and reduce the power loss. ROF system need high-repetition-rate and multi-wavelength short pulse source to work as carriers of multi-channel millimeter waves, so high-quality, multi-wavelength and low cost sources becomes an important research content. Currently, several mature sources are in application [1-8]. The first one, each channel uses one laser as signal source. This kind of system is simple and stable, it is high cost when system needs lots of channels, and difficult to adjust wavelength for aligning to ITU-T standard wave length. The second one, using the spontaneous emission spectrum of luminous diode such as Super Fluorescent Diode and Erbium-doped fiber amplifier as signal source, it can provide multi-wavelength carriers simultaneously, but is hard to meet requirement of long distance transmission because of its high noise and low coherence. The third one, slicing super-continuum (SC) to generate multi-carriers, this method can greatly increase signal to noise ratio (SNR), reduce measurement time, and broaden spectrum measurement domain due to SC's large output power, wide flat bandwidth and high spatial coherence. In 2006, Teppei Nakasyotani et al. first proposed and implemented this method to generate multi-millimeter-carriers with low phase noise [4]. In experiment, they used mode-lock semiconductor laser as seed source to generate comb spectrum directly. However, the limitations of fabrication technology and output power restrict the properties of multi-wavelength-carriers. In addition, the wavelength of each channel is relatively fixed, and the system is not flexible. In order to overcome these shortcomings, we propose a new method to generate the multi-carriers for WDM-ROF system by slicing super-continuum with SFBG. Because each wavelength of SFBG can be easily set by relative length of controlling grating area and non-grating area, this method can greatly improve the system stability.

In this paper, we propose a new mm-wave multi-carrier generation method by heterodyne modulation without ultra-high-speed modulator, and the system frequency can be easily controlled by slicing spacing. We also analytically study the impact of carrier-to-carrier ratio (CCR) defined as the ratio of the optical power in every two carriers on the overall WDM-ROF system performance.

2. Theory model

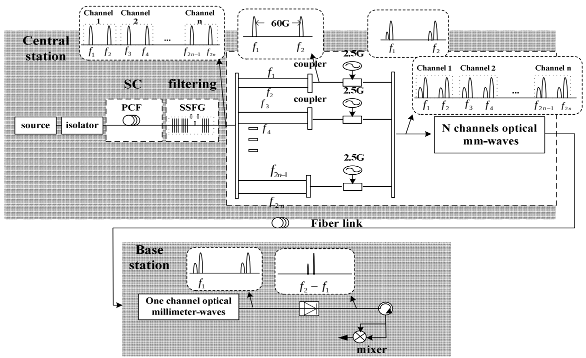


Fig. 1. Schematic of analytical model.

The analytical model for mm-wave multi-carriers generation of WDM-ROF system based on broadband spectrum slicing principle is shown in Fig. 1. Here we mainly focus on generation of SC and comb filtering using SFBG. A seed short pulse is firstly generated from a femto-second Semiconductor mode-locked laser, which is subsequently coupled into HNL-PCF in order to generate SC, then utilizing SFBG designed and fabricated by us to filter to obtain multi-wavelength-spectrum. As shown in Fig. 1, every two wavelengths filtered out can be used as one channel ROF-carrier. The multi-channel multi-carriers for WDM-ROF system can be generated by one seed laser simultaneously using above method. We assume frequencies of two waves in one channel as f_1 and f_2 and optical field after modulating digital signal $A(t)$, then generated optical mm-wave signals can be described as follows [4,5]:

$$E_1(t) = A(t)[a_1 e^{j\omega_1 t+\phi_1} + a_2 e^{j\omega_2 t+\phi_2}] \tag{1}$$

where a_1, a_2 and ϕ_1, ϕ_2 are the amplitude and initial phase of the carriers.

When the millimeter signal transmits through single mode fiber, the carriers are broadened by dispersion effect. Optical field can be described as following equation:

$$E(z,t) = a_1 A\left(t-\omega_1^{-1}\beta(\omega_1)z\right)e^{j\left[\omega_1 t-\beta(\omega_1)z+\varphi_1\right]-\alpha z} + a_2 A\left(t-\omega_2^{-1}\beta(\omega_2)z\right)e^{j\left[\omega_2 t-\beta(\omega_2)z+\varphi_2\right]-\alpha z} \tag{2}$$

In the base station, we change mm-wave signals into optical electric current using photodetector after transmitting, and the corresponding case is

$$I_1(t) = \mu\left|E(z,t)\right|^2 = \mu A^2(t)\left\{a_1^2 + a_2^2 + 2a_1 a_2 \cos\left[(\omega_1-\omega_2)t + \beta(\omega_1)z - \beta(\omega_2)z + \varphi_2 - \varphi_1\right]\right\} \tag{3}$$

Because the transmission speeds of two carriers are different according to equation: $\nu_i = \omega_i \beta^{-1}(\omega_i)$, $(i=1,2)$, digital signals A_1 and A_2 carried by two different carriers will depart gradually, which means code edges A_1 and A_2 will wake off when transmitting in fiber. The wake-off time can be expressed by

$$\begin{aligned}\Delta t &= \frac{\beta(\omega_1)}{\omega_1}z - \frac{\beta(\omega_2)}{\omega_2}z \\ &= \frac{-(\omega_2-\omega_1)z}{\omega_1\omega_2}\left\{\frac{\omega_1+\omega_2}{2}\beta'\left(\frac{\omega_1+\omega_2}{2}\right) - \beta\left(\frac{\omega_1+\omega_2}{2}\right) + \frac{\omega_2-\omega_1}{4}\left[(\omega_1+\omega_2) - \frac{\omega_2-\omega_1}{2}\right]\beta'\left(\frac{\omega_1+\omega_2}{2}\right)\right\} \\ &\approx -(\omega_2-\omega_1)\beta'\left(\frac{\omega_1+\omega_2}{2}\right)z \\ &= \lambda_c^2 D c^{-1}(f_2-f_1)z\end{aligned} \tag{4}$$

Walk-off effect of code edge is directly proportional to RF frequency, fiber dispersion and fiber length. For bit Rate given, the rectangle pulse duty cycle is η, and the code width is $\tau = \eta / R$. When $\Delta t \to \tau$, two signal pulses will be separated completely, its eye diagram will be close, and the transmission distance will be limited by

$$z < l \equiv \frac{\eta c}{R\lambda_c^2 D(f_2-f_1)} \tag{5}$$

The transmission distance limit is directly proportional to η and inversely proportional with bit rate, dispersion and RF frequency. Because the amplitude of output signal pulse equals to product of two carriers' amplitude, the wake off effect of two carriers will cause the width of signal to become narrower gradually. When the distance is close to l, the pulse width can be neglected. In practical system, when the fiber length $z > l/2$, the pulse width becomes narrower quickly with the performance of signal being worse. In this simulation, we will use the signals with different bit rate and modulation format, and the result shows that the BER of output signal is also related to the amplitude difference of two carriers. Considering above factor, we define CCR as:

$$CCR = 10\log_{10}\left(\frac{a_1}{a_2}\right) \tag{3}$$

where both a_1 and a_2 are the powers corresponding to different wavelengths. It can be known that the obtained power of RF signal is influenced by CCR because of $a_1^2 + a_2^2 \geq 2a_1a_2$ even if the overall input power is stable. Therefore, the two wavelengths with the smallest power difference can be recovered from the biggest RF signal power, and the flatness of SC and identical reflection of SFBG are two main factors on impact the system performance.

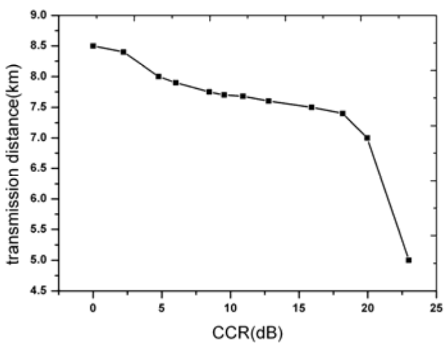
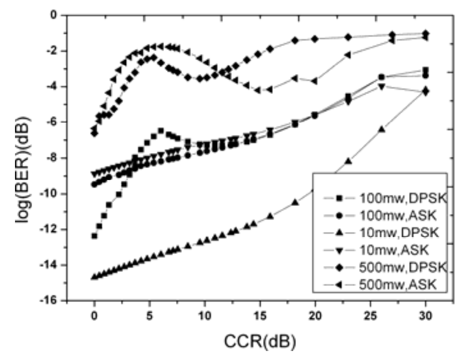


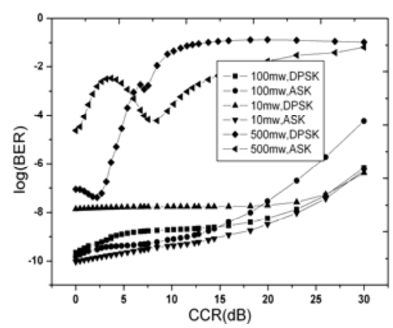
Fig. 2. Transmission distance versus optical CCR.

The single-channel simulation containing two 60-GHz-spaced sub-carriers has been carried out to verify the analytical model. The femto-second pulse as optical single source for the WDM-ROF system is launched into a high-nonlinear fiber to generate super-continuum, a SFBG is spliced, and two adjacent wavelengths are chosen as two sub-carriers in one channel. Assuming that the sum power of the two waves in one channel to be 10 mw, 100 mw, and 500 mw after EDFA, respectively, they are kept to be constant, and only the proportion of these two input powers are changed. As shown in Fig.2, the optimum operating condition occurs at an optical CCR of 0dB which agrees well with the theory analysis. Fig. 2. shows that CCR influences the transmission distance due to lager dispersion caused by difference of sub-carriers.

The digital signals of ASK and DPSK performance carried by millimeter-wave are introduced to analyze the CCR influence on BER. According to equation (5), it can be shown that the length of single mode fiber with the bit rate equaling to 5Gbit/s is much shorter than that when the bit rate equals to 2.5Gbit/s because of dispersion effect. As shown in Fig.3, the relative amplitude is the crucial factor of achieving high BER. In Fig.3 (a), for 5Gbit/s bit rate, when the total power of two sub-carriers is 500mw, the BER is worse than that when the total power is 100mw and 10mw. The similar situation is presented in Fig.3 (b) with bit rate of 2.5Gbit/s. Because the signal with lower bit rate transmits a longer distance, the lower power of sub-carrier can improve the BER of output signal. If the total power of two sub-carriers keeps constant, the BER is best, and the signal with higher bit rate is affected greatly when CCR is 0. Comparing (a) and (b), we can also known that the BER performance of DPSK format is better than that of ASK. Based on above analysis, we can see that the CCR is an important parameter for evaluating the performance of ROF system.



(a)



(b)

Fig. 3. BER versus optical CCR with different bit rate and modulation format (a) bit rate is 5Gbit/s (b)bit rate is 2.5Gbit/s.

In our scheme, in order to achieve the optimum value of CCR, the flat SC is obtained through choosing suitable fiber, and the SFBG with large number sampled periods and small length of sub-grating in each sampled period is used to filter with the initial phases of adjacent wavelengths for one channel being kept to be equal. The performance of WDM-ROF system in the all-optical scheme to generate multichannel Optical Millimeter-Waves can achieve optimum.

3. Experiment results and discussion

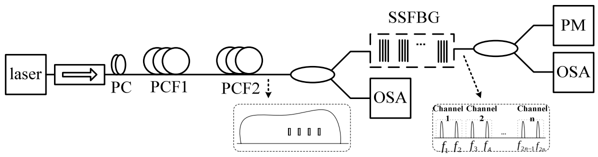


Fig. 4. The experiment setup for SC generation and SFBG. filtering.

The experiment setup for multi-wavelength-carriers generation of WDM-ROF system based on broadband spectrum slicing principle is shown in Fig. 4. A seed short pulse was firstly generated from a femto-second Semiconductor mode-locked laser, which was subsequently coupled into two passages of 5-m-long HNL-PCF with different dispersion (which is recorded as positive-PCF and negative-PCF, P-PCF and N-PCF, respectively) in order to generate SC, then utilize SFBG designed and fabricated by us to comb filter to obtain multi-wavelength-spectrum. As shown in Fig. 1, every two wavelength filtered out can be used as one ROF-carrier. The multi-channel-carriers for WDM-ROF system can be generated by one seed laser simultaneously using above method.

3.1 Generation of flat SC

Fig. 5 shows SC generated when the average input powers of femto-second pulses are 15.9 dB, 17.9 dB, 19.7 dB and 21.5 dB. When the average output powers increase as high as 21.5 dB, the power fluctuation of SC is smaller than 0.15 dB around -47.17 dB in the wavelength range of 1548.51nm-1560.61nm of WDM optical communication system with 16 channels and 100G spacing, which have a benefit for further comb filtering. In our scheme, CCR easily reach its optimum value to ensure the better performance of WDM-ROF system.

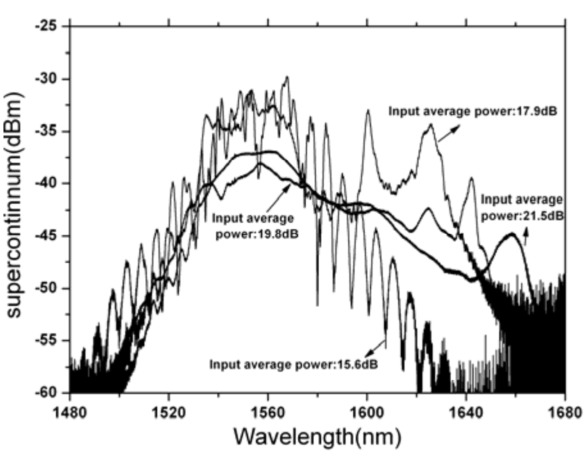


Fig. 5. SC evolution after HNL-PCF.

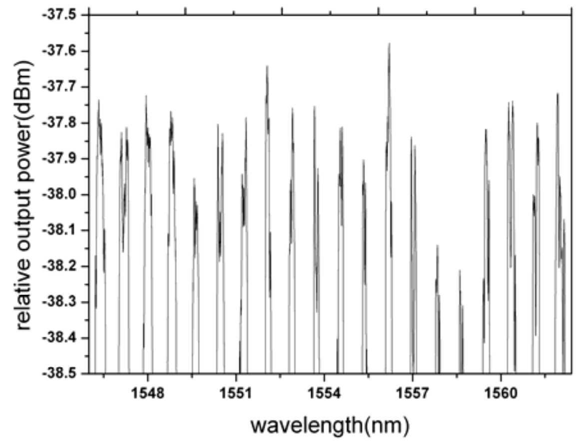


Fig. 6. mm-wave multi-carriers after splicing.

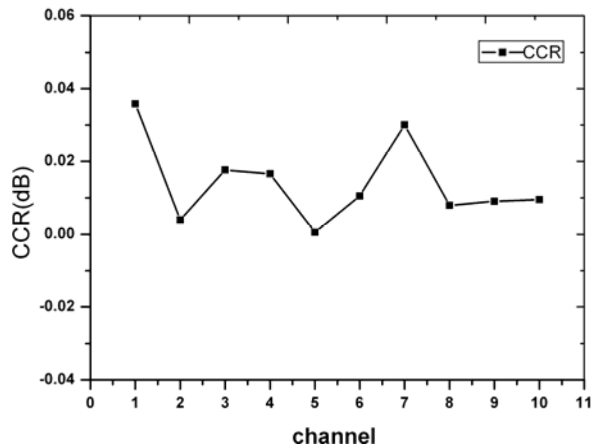


Fig. 7. CCR in each channel.

3.2 Small CCR of each channel

We obtained multi-wavelength source which is suitable for WDM-ROF by comb filtering generated SC using SFBG. As shown in Fig. 7, there are more than twenty wavelength with less than 0.3 dB around -38.9 dB of peak power fluctuation and smaller than 0.1nm width. Fig. 8. shows that CCR is small enough to ensure SNR of modulated signal with highest difference of 0.035 dB.

4. Conclusions

A new scheme is proposed to generate mm-wave in WDM-ROF system based on SC, and the SSFBG comb filtering and two waves heterodyning are shown. The scheme has excellent performance such as simple structures, multi-channel carrier generation, multi-frequency mm-wave generation, easily controlled CCR by choosing suitable parameters of SFBG and fiber.

Acknowledgments

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