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A millimeter-wave radio-over-fiber system for overcoming fiber dispersion-induced signal cancellation effect

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Millimeter-wave (mm-wave) radio over fiber (ROF) using dispersive single-mode fiber is susceptible to signal cancellation effect at the output of the uni-travelling carrier photodiode at the base station (BS). The fiber dispersion effect produces different phase shifts of the sidebands of the intensity-modulated lightwave which can produce a cancellation of the output signal when mixed with the optical carrier. In this paper, we propose and analyze a novel scheme of mm-wave ROF which uses microwave modulation at the central station (CS) and frequency upconversion before the BSs. This scheme can overcome fiber dispersion-induced signal cancellation effect.

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A survey of available references indicates that extensive research works are being done on millimeter-wave (mm-wave) radio-over-fiber (ROF) system all over the globe[1-12]. Transmission of optical and mm-wave signals over a fiber-optic link has been studied[3,5,13-15] well in the last decade. Researches on the generation, modulation and detection of signals in ROF systems have been carried out in the recent past[5,6]. Applications of frequency upconversion in ROF system have been studied[16]. Effects of dispersion, laser linewidth and laser phase noise have been investigated[17].

The intensity-modulated lightwave has an optical carrier and two principal sidebands in its spectrum. The upper and lower optical sidebands suffer different phase shifts due to the group velocity dispersion (GVD) of the single-mode fiber during their propagation through the fiber. The GVD-induced phase shift depends on the modulation frequency parabolically. If we use mm-wave modulation of the lightwave in the central station (CS), the dispersion-induced phase shift becomes considerable even when the fiber length is less than 1 km. When the sidebands are mixed with the optical carrier in the photodiode at the base station (BS), the output signal is reduced, which depends on the mm-wave frequency and the fiber length, and the detected signal amplitude can go down to zero level. It is called fiber dispersion-induced signal cancellation effect.

In this paper, a novel scheme of mm-wave ROF is proposed using an optical comb source operating at central wavelength of 1.55 μm, where a group of optical comb lines are intensity modulated by a group of microwave subcarriers, and the microwave-modulated optical signals are transported from the CS to the proximity of the BSs through a single-mode fiber. At the intermediate station close to the BSs, the microwave-modulated lightwaves are intensity modulated again by a 60 GHz local mm-wave signal in a polymer modulator. It produces frequency upconversion of the modulation signal from microwave to mm-wave. The unique advantage of the proposed scheme is that the chance to detect the signal cancellation at the BS is reduced. The scheme is very useful when the BSs are distantly located from the CS in the case in metropolitan cities.

A schematic diagram of the proposed mm-wave ROF is shown in Fig.1. A source of optical comb lines operating at the central wavelength of 1.55 μm is taken, which delivers n optical carriers with wavelengths of λ_1, λ_2, λ_3,$\cdots$,λ_n and a typical line spacing of 50 GHz. Each optical carrier is intensity modulated in a lithium niobate Mach-Zehnder light intensity modulator (M-ZLIM). A modulator is assumed to modulate a particular optical carrier of λ_k by the microwave signal with frequency of f_{mk}. In practice, the modulation signal is a band-limited cable television (CATV) signal. The n intensity-modulated lightwaves are combined in an optical combiner, and the combined output from the CS propagates through a single-mode fiber to the BSs. Before the signal distribution among the BSs, the microwave signal is upconverted to 60 GHz mm-wave modulation. The frequency upconverter is a polymer modulator which produces light

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intensity modulation by the local mm-wave signal at 60 GHz. The mm-wave modulated lightwaves are amplified in an erbium doped fiber amplifier (EDFA) which typically has the gain of 20 dB and the bandwidth of 8 nm. The amplified lightwave is splitted in a 1 × n optical power splitter, and the optical signals are distributed among the BSs. In the BS, the mm-wave modulated lightwave is detected by a photodiode, and the desired mm-wave signal is filtered by a mm-wave band pass filter. The mm-wave signal carrying the CATV signal is radiated by an antenna over the subscriber premises. Since the initial modulation is in the microwave frequency region, the effect of fiber dispersion on the optical sidebands can be smaller when the mm-wave modulation is used in the CS. So the signal cancellation effect induced by fiber dispersion can be avoided in this scheme.

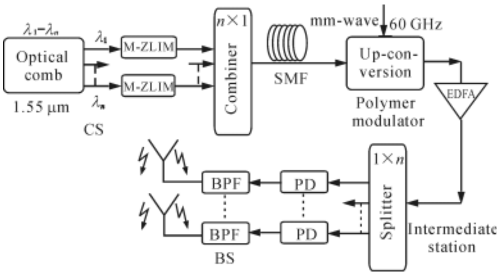

Fig.1 Schematic diagram of the proposed mm-wave ROF system

We first consider that the signal mitigation effect is due to fiber dispersion. The electric field of the optical carrier in the intensity-modulated lightwave can be represented by

$$E_c(t) = E_{c0}\sin\omega_c t \ , \tag{1}$$

while the upper and lower sidebands are expressed as

$$E_{SB}(t) = E_{c0} m \sin(\omega_c \pm \omega_m)t \ , \tag{2}$$

where E_{c0} is the electric field amplitude, and $2m$ is the intensity modulation index. We assume $2m << 1$. The time which is taken by the optical carrier in propagating through a single-mode fiber with length of L is

$$t_c = \frac{L}{v_g} \ , \tag{3}$$

where v_g is the group velocity of the carrier wave. Now,

$$v_g = \frac{\partial\omega}{\partial\beta} \ , \tag{4}$$

where ω is the circular frequency of the lightwave, and β is the phase shift constant. Since the time of propagation of the lightwave through the fiber is a function of ω, we can write

$$t(\omega_c \pm \omega_m) = t_c \pm \frac{\partial t}{\partial \omega}\Big|_{\omega=\omega_c} \omega_m = t_c \pm L\beta_2\omega_m \ , \tag{5}$$

where $\beta_2 = \frac{\partial^2 \beta}{\partial \omega^2}\Big|_{\omega=\omega_c}$ is known as the GVD parameter. In the photodiode, the upper sideband and lower sideband are mixed with the carrier, and the difference frequency signal is generated which appears as the detected signal at the photodiode output. The upper sideband and the carrier produce a signal as

$$E_u(t) = \frac{1}{2} m E_{c0}^2 \cos(\omega_m t_c + \omega_c L\beta_2\omega_m + L\beta_2\omega_m^2) \ . \tag{6}$$

Similarly, the lower sideband and the carrier produce an output signal as

$$E_l(t) = \frac{1}{2} m E_{c0}^2 \cos(\omega_m t_c + \omega_c L\beta_2\omega_m - L\beta_2\omega_m^2) \ . \tag{7}$$

The sum of these two signals of $E_u(t)$ and $E_l(t)$ appearing at the output is proportional to cos($L\beta_2\omega_m^2$). Depending on the values of L and ω_m, the value of the term $L\beta_2\omega_m^2$ can be $\pi/2$, and in this case the detected signal at the output becomes zero. It is called the cancellation of the detected signal. If the value of ω_m is large, which is more likely for mm-wave modulation around 60 GHz, the value of the factor $L\beta_2\omega_m^2$ may be $\pi/2$ or even greater, and there is a chance to have the signal cancellation. If we use microwave modulation (typically, less than 10 GHz) in the CS, the adverse effect can be reduced, and the detected signal will not be cancelled. The dispersion parameter D is related with β_2 by the relation of $D = -\frac{2\pi c}{\lambda^2}\beta_2$, where c is the vacuum velocity of light, and λ is the wavelength of the lightwave. As an example, taking L=1 km, λ=1.55 μm, D=17 ps/(km·nm) and f_m=5 GHz, we get $L\beta_2\omega_m^2$=0.021 rad, whereas with f_m=60 GHz, we get $L\beta_2\omega_m^2$=3.08 rad.

A comb line with wavelength of λ_k is intensity modulated by a microwave signal with frequency of ω_{mk} in a lithium niobate M-ZLIM. Assuming the linear operation of the M-ZLIM with a direct current (dc) bias of $\frac{1}{2}V_\pi$, the intensity of this signal can be represented as

$$I_k(t) = \frac{1}{2} I_0 (1 + m_1 \sin\omega_{mk} t) \ , \tag{8}$$

where V_π is the half-wave voltage of the modulator, and I_0 is the peak intensity of the modulated lightwave. Also, $m_1 = \pi V_{m0}/V_\pi$ is the intensity modulation index, and ω_{mk} is the microwave modulation frequency corresponding to the k-th channel. The mm-wave polymer modulator is driven by a local mm-wave oscillator at 60 GHz, and produces a second modulation of the input microwave-modulated lightwave. The light intensity of the k-th lightwave from the polymer modulator can be written as

$$I'_k(t)=\frac{1}{2}I_k(t)(1+m_2\sin\omega_{\mathrm{LO}}t)=\\ \frac{1}{4}I_0[1+m_1\sin\omega_{mk}t+m_2\sin\omega_{\mathrm{LO}}t+\\ \frac{1}{2}m_1m_2\cos(\omega_{\mathrm{LO}}+\omega_{mk})t-\\ \frac{1}{2}m_1m_2\cos(\omega_{\mathrm{LO}}-\omega_{mk})t]\ . \tag{9}$$

This intensity-modulated light is amplified in the EDFA and the amplified signal is power divided in each of the p BSs. In the BS, there is a photodiode which detects the intensity modulation, and the detected signal passes through a band pass filter (BPF) with the center frequency of $\omega_{\mathrm{LO}}+\frac{1}{2}(\omega_{mn}+\omega_{m1})$ and the bandwidth of $(\omega_{mn}-\omega_{m1})$, where $\omega_{m1}<\omega_{m2}<\omega_{m3}<\cdots<\omega_{mn}$. The BPF delivers the signals with the frequencies of $\omega_{\mathrm{LO}}+\omega_{m1}$, $\omega_{\mathrm{LO}}+\omega_{m2}$,$\cdots$, $\omega_{\mathrm{LO}}+\omega_{mn}$ at the output As an example, taking f_{LO}= 60 GHz, $n = 5$, ω_{m1} = 1 GHz, ω_{m2}= 2 GHz,$\cdots$, ω_{m5} = 5 GHz, the center frequency of the BPF is at 63 GHz, and its bandwidth is 4 GHz. The mm-wave signals at the output have the frequencies of 61 GHz, 62 GHz, 63 GHz, 64 GHz and 65 GHz. These signals are radiated from each BS. One can choose the other group of mm-waves with the frequencies of $(\omega_{\mathrm{LO}}+\omega_{mk})$ for k=1, 2, 3, 4, 5, as well by taking a different BPF with center frequency of $[\omega_{\mathrm{LO}}+\frac{1}{2}(\omega_{m1}+\omega_{mn})]$ and with a bandwidth of $(\omega_{mn}-\omega_{m1})$.

The optical beat interference (OBI) in mm-wave ROF can arise from the beating of two wavelength division multiplexing (WDM) optical carriers carrying mm-wave modulation. The OBI can be avoided by choosing the inter-carrier frequency separation and the mm-wave local frequency suitably to make sure that the difference of these two frequencies is well below the mm-wave local frequency of ω_{LO}. As an example, taking the inter-carrier separation of 50 GHz and the mm-wave local frequency of 60 GHz, the OBI can be avoided because the difference frequency of 10 GHz falls outside the pass band of the band pass filter.

Another source of interference in mm-wave ROF is the mixing product signals which can appear along with the desired signal. The mixing products originate from the nonlinearities of the microwave and mm-wave modulators. In the presence of modulator nonlinearity, the intensity of the modulated lightwave from the polymer modulator can be expressed as

$$I'_k(t)=\frac{1}{4}I_0[1+2\sum_{p=1}^{\infty}J_{2p-1}(m_1)\sin(2p-1)\omega_{mk}t]\times\\ [1+2\sum\nolimits_{r=1}^{\infty}J_{2r-1}(m_2)\sin(2r-1)\omega_{\mathrm{LO}}t]. \tag{10}$$

As an example, taking the number of WDM optical channels as 5, f_{LO}=60 GHz, the lowest microwave modulation frequency of 1 GHz and the microwave channel spacing of 1 GHz, an interferring product term proportional to $\frac{1}{2}J_3(m_1)\times J_1(m_2)I_0$ appears at 63 GHz, and a term proportional to $\frac{1}{2}J_5(m_1)\times J_1(m_2)I_0$ appears at 65 GHz. The desired signal term is proportional to $\frac{1}{2}J_1(m_1)J_1(m_2)I_0$. $m_1=\pi V_{m0}/V_{\pi}$ is the modulation index of all the microwave channels, and V_{m0} is the microwave modulation signal voltage which is assumed to be the same for all the channels. $m_2=\pi V_{\mathrm{LO}}/V_{\pi p}$ is the modulation index of the mm-wave polymer modulator with the half-wave voltage of $V_{\pi p}$. V_{LO} is the mm-wave local signal voltage. The interference-to-signal power ratio is given by $\frac{J_3^2(m_1)}{J_1^2(m_1)}$ for the 63 GHz channel and by $\frac{J_5^2(m_1)}{J_1^2(m_1)}$ for the 65 GHz channel. The variation of the calculated interference-to-signal power ratio as a function of the microwave intensity modulation index is shown in Fig.2.

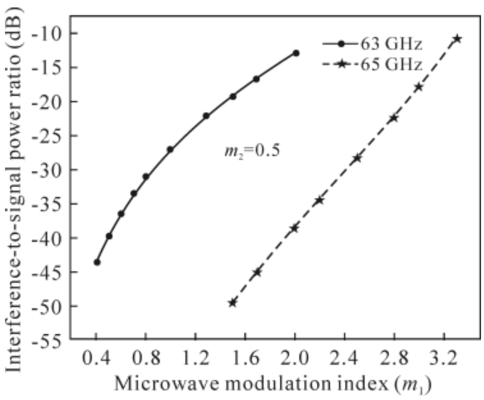

Fig.2 Calculated variation of interference-to-signal power ratio with the microwave intensity modulation index

To keep the interference-to-signal power ratio less than -25 dB in a channel, the microwave intensity modulation index can be safely chosen up to 1.

A novel scheme of mm-wave ROF is proposed and analyzed, which overcomes fiber dispersion-induced signal cancellation effect. This is due to the fact that the microwave modulation frequency, which is much smaller than the mm-wave signal frequency, produces much less difference in phase shifts of the two optical sidebands. The mm-wave ROF is useful for the transmission of wireless CATV signals and data to the subscriber premises through the mm-wave link.

References

[1] V. Sharma, A. Singh and A. K. Sharma, Optik- Int. J. of Light Electron. Opt. **123**, 338 (2012).

[2] V. Sharma, A. Singh and A. K. Sharma, Optik **121**, 1280 (2010).

[3] H. C. Chien, Y. T. Hsueh, A. Chowdhury, J. Yu, G. Chang and G. K. Chang, Journal of Lightwave Technology **28**, 2230 (2010).

[4] V. Sharma, A. Singh and A. K. Sharma, Optics and Lasers in Engineering **47**, 1145 (2009).

[5] T. Wang, M. Chen, H. Chen and S. Xie, Opt. Commun. **282**, 3360 (2009).

[6] J. Yin, K. Xu, D. Wang and J. T. Lin, J. Chin. Uni. Posts and Telecommun. **16**, 62 (2009).

[7] M. F. Huang, J. Yu, Z. Jia and G. K. Chang, Journal of Lightwave Technology **26**, 2653 (2008).

[8] Y. Takahashi, M. Matsuba, T. Sono, S. Sadoshima, H. Toda, T. Kuri and K. Kitayama, An Effect of Downlink Optical Sideband Suppression on Uplink Transmission in Full-Duplex DWDM Millimter-Wave-Band Radio Over Fiber, IEEEE International Topical Meeting on Microwave Photonics, 112 (2007).

[9] T. Kurniawan, A. Nirmalathas, C. Lim, D. Novak and R. Waterhouse, IEEE Trans. Microwave Theory Techniques **54**, 921 (2006).

[10] P. C. Won, W. Zhang and J. A. R. Williams, Self Phase Modulation Dependent Dispersion Mitigation in High Power SSB and DSB+ Dispersion Compensated Modulated Radio Over Links, Proceedings of IEEE MTTS International Microwave Symposium, 1947 (2006).

[11] C. Lim, M. Attygalle, A. Nirmalathas, D. Novak and R. Waterhouse, IEEE Trans. Microwave Theory Tech. **54**, 2181 (2006).

[12] F. Smyth, A. Kaszubowska and L. P. Barry, Opt. Commun. **231**, 217 (2004).

[13] X. Liu, Z. Liu, J. Li, T. Shang and J. Zhao, Opt. Commun. **283**, 3129 (2010).

[14] J. G. Zhao, Z. Liu, X. Liu, T. Shang and P. Yue, Opt. Commun. **282**, 4353 (2009).

[15] J. Ma, J. Yu, C. Yu, X. Xin, H. Huang and L. Rao, Opt. Commun. **281**, 2799 (2008).

[16] J. Palaci, J. Herrera and J. Marti, EAM-SOA-Based Millimeter Wave Frequency Upconversion for Radio-Over-Fiber Applications, International Topical Meeting on Microwave Photonics, 1 (2009).

[17] R. Lin and M. Xiu, Effect of Laser Linewidth on Millimter-Wave Radio-Over Fiber System Employing Optical Frequency Multiplying, Conference on Lasers and Electro-optics, Pacific Rim, 1 (2007).