Simplified Millimeter-wave Radio-over-fiber System Using Optical Heterodyning of Low-cost Independent Light Sources and RF Homodyning at the Receiver

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***Abstract*— A simplified, cost-effective millimeter-wave radio-over-fiber system is proposed by heterodyning two independent low-cost light-sources and RF homodyning at the receiver that suppresses phase-noise effects. Proposed system avoids phase/frequency locking, high-speed modulators and local oscillators/mixers in CO and BSs.**

I. Introduction

Radio-over-fiber (RoF) is a promising solution to deliver broadband wireless services in the access networks at millimeter-wave (mm-wave) frequencies [1]. Due to higher propagation losses at these frequencies, a large number of remote antenna base stations (BS) is required within a small geographic area. Therefore, cost-effective and simplified architectures are essential for their successful commercial deployment. Schemes for the generation and distribution of mm-wave RoF signals can be categorized into two main groups. In the first approach, two optical tones separated by the desired mm-wave frequency are generated using frequency and/or phase locking of light sources. These techniques include optical phase locking or injection locking of two laser diodes [1-3], mode-locked lasers [4] and dual-mode lasers [5]. In these methods, complex locking arrangements and synthesizers or local oscillators (LO) are essential to avoid phase-noise-induced instability which puts stringent requirements on system performance. In the second approach, a single light source is utilized to generate either optical single sideband with carrier (OSSB+C) or carrier-suppressed double sideband (CS-DSB) signals by using expensive and high speed modulators with rigorous filtering arrangements [6-7]. Such high speed modulators at mm-wave frequencies are still maturing as it exhibits poor performance in terms of stability and sensitivity. Moreover, these systems require costly high frequency LO's and associated complex mixing circuitry.

Recently, we proposed a simplified architecture where a frequency locked dual tone fiber laser was heterodyned, and then self mixed/homodyned to recover the baseband data, thereby avoiding the need for microwave synthesizers or LO's and high speed optical modulators [8]. Also the introduction of self mixing/homodyning technique in this system effectively suppresses the effects of phase-noise effects [9].

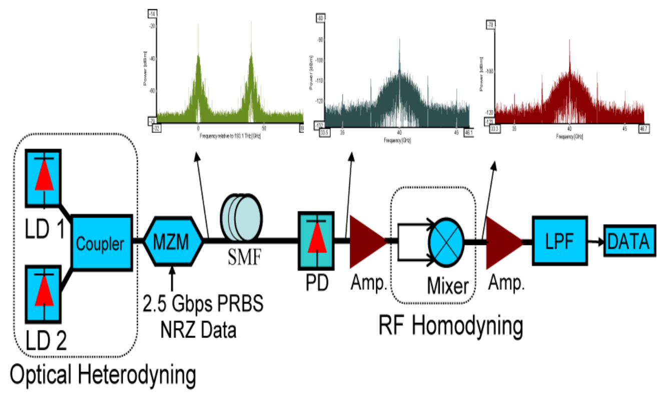

Figure 1. Proposed RoF system configuration

However, fiber laser used in our system required precise tuning of fiber Bragg gratings and physical stabilization.

This paper investigates a simpler approach to generate the mm-wave signal by optically heterodyning two independent, off-the-shelf, low cost light sources such as distributed feedback (DFB) lasers and then self mixing/homodyning the detected RF signals that effectively avoids the potential challenges from phase-noise effects. The separation of the two lasers at 40 GHz is used as the mm-wave frequency in our system for 2.5 Gbps amplitude-shift-keyed (ASK) non-return-to-zero (NRZ) data. A theoretical analysis followed by simulation results show that the proposed system can successfully avoid all the stringent requirements of phase or frequency locking, high speed modulators and/or LO's both at the central office (CO) and the BSs. Bit-error-rate (BER) performances due to varying frequency separations of two lasers, linewidths, relative intensity noise (RIN), and data rates are presented to show the performance of our proposed system.

II. Theory

Fig. 1 presents our proposed RoF system configuration. Electric fields of two independent lasers in our system can be represented as $E_1 \exp j(2\pi \upsilon_1 t)$ and $E_2 \exp j(2\pi \upsilon_2 t)$.

Here, E_1 and E_2 are the peak amplitudes of the electric fields and υ_1 and υ_2 are optical frequencies of two lasers such that $(\upsilon_1 - \upsilon_2)$ is the desired mm-wave frequency. For simplicity, in our analysis we assume $E_1 = E_2 = 1$ and the modulating signal is sinusoidal.

The complex field envelope of the single-drive Mach-Zehnder modulated optical modes can be written as

$$A_1(t) = \exp j\left[2\pi \upsilon_1 t + \frac{1}{2}(m\cos\omega_m t + \theta) + \phi_1\right] \tag{1}$$

$$A_2(t) = \exp j\left[2\pi \upsilon_2 t + \frac{1}{2}(m\cos\omega_m t + \theta) + \phi_2\right] \tag{2}$$

where m is the modulation index of the single-drive Mach-Zehnder modulator (MZM), ω_m is the angular frequency of the modulated mm-wave signal and θ is the mosulator bias phase shift. ϕ_1 and ϕ_2 are the phase noise of the two independent lasers.

Mach-Zehnder modulated complex envelope representation of both the optical modes as in equation (1) and (2) now can be expressed in terms of Bessel functions of the first kind as

$$A_1(t) = \sum_{n=-\infty}^{\infty} j^n J_n\left(\frac{m}{2}\right)\exp j\left[2\pi(\upsilon_1 + nf_m)t + \frac{\theta}{2} + \phi_1\right] \tag{3}$$

$$A_2(t) = \sum_{n=-\infty}^{\infty} j^n J_n\left(\frac{m}{2}\right)\exp j\left[2\pi(\upsilon_2 + nf_m)t + \frac{\theta}{2} + \phi_2\right] \tag{4}$$

where f_m is the modulating frequency, $J_n(x)$ is the Bessel function of the first kind of order n and argument x to realize all order of sidebands due to external modulation.

The transfer function of the dispersive component of the single mode fiber (SMF) is given as

$$H(j\omega) = \exp\left(j\frac{1}{2}\beta_2 z\omega^2\right) \tag{5}$$

where β_2 is the second-order fiber dispersion coefficient due to chromatic dispersion and z is the length of the fiber.

The complex fields of the modulated signal after transmission through the dispersive fiber can be represented as

$$A_{f_1}(t) = \sum_{n=-\infty}^{\infty} j^n J_n(m)\exp j\left[2\pi(\upsilon_1 + nf_m)t + \frac{\theta}{2} + \phi_1\right] \cdot \exp\left(j\frac{1}{2}\beta_2 z n^2 \omega_m{}^2\right) \tag{6}$$

$$A_{f_2}(t) = \sum_{n=-\infty}^{\infty} j^n J_n(m)\exp j\left[2\pi(\upsilon_2 + nf_m)t + \frac{\theta}{2} + \phi_2\right] \cdot \exp\left(j\frac{1}{2}\beta_2 z n^2 \omega_m{}^2\right) \tag{7}$$

The complex conjugate of equation (6) and (7) becomes

$$A^*_{f_1}(t) = \sum_{p=-\infty}^{\infty} j^{-p} J_p(m)\exp\left(-j\left[2\pi(\upsilon_1 + pf_m)t + \frac{\theta}{2} + \phi_1\right]\right) \cdot \exp\left(-j\frac{1}{2}\beta_2 z p^2 \omega_m{}^2\right) \tag{8}$$

$$A^*_{f_2}(t) = \sum_{p=-\infty}^{\infty} j^{-p} J_p(m)\exp\left(-j\left[2\pi(\upsilon_2 + pf_m)t + \frac{\theta}{2} + \phi_2\right]\right) \cdot \exp\left(-j\frac{1}{2}\beta_2 z p^2 \omega_m{}^2\right) \tag{9}$$

Finally, assuming the two fields are collinearly polarised, the generated electrical signal at the output of photodetector (PD) is derived as

$$i_p(t) = \Re \times \left[\left(A_{f_1}(t) + A_{f_2}(t)\right) \times \left(A^*_{f_1}(t) + A^*_{f_2}(t)\right)\right] \tag{10}$$

where $\Re$ is the responsivity of the PD. Now, the beating process takes place in the PD among the generated sidebands and optical carriers. Beating between two optical modes results the generation of our desired electrical signal at mm-wave range along with different orders of electrical harmonic components.

After some manipulations, the exact analytic expression after the PD incorporating all orders of sidebands of the MZM-based RoF link using two independent laser sources can be written as

$$i_p(t) = \Re \times \sum_{n=-\infty}^{\infty}\sum_{p=-\infty}^{\infty} j^{(n-p)} J_n(m) J_p(m) \times \exp j\left(n^2 - p^2\right)\left(0.5\beta_2 z\omega^2{}_m\right)$$

$$\times\left\{\exp j\left[4\pi(n-p)f_m t + 2\theta\right] + \exp j\left[2\pi\{(\upsilon_1 - \upsilon_2) + (n-p)f_m\}t + (\phi_1 - \phi_2) + \theta\right]\right.$$

$$\left. + \exp j\left[2\pi\{(\upsilon_2 - \upsilon_1) + (n-p)f_m\}t + (\phi_2 - \phi_1) + \theta\right]\right\} \tag{11}$$

The second-to-the-last term in equation (11) clearly shows the desired mm-wave frequency at $(\upsilon_1 - \upsilon_2)$ together with the harmonic components and the phase noise $(\phi_1 - \phi_2)$ as a result of beating of two lasers.

Squaring or self-mixing equation (11) would generate higher order components and would therefore reduce the effects of phase noise in the system. Because, when the detected phase noise term $(\phi_1 - \phi_2)$ is squared, the total amount of noise would be negligible in a practical case as the

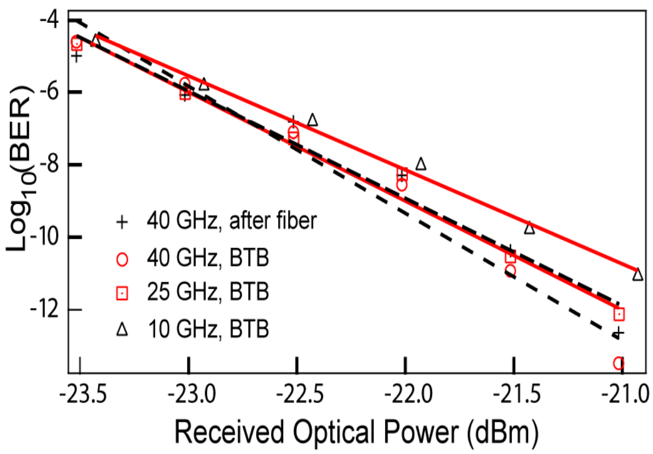

Figure 2. BER curves for different frequency spacing between two lasers

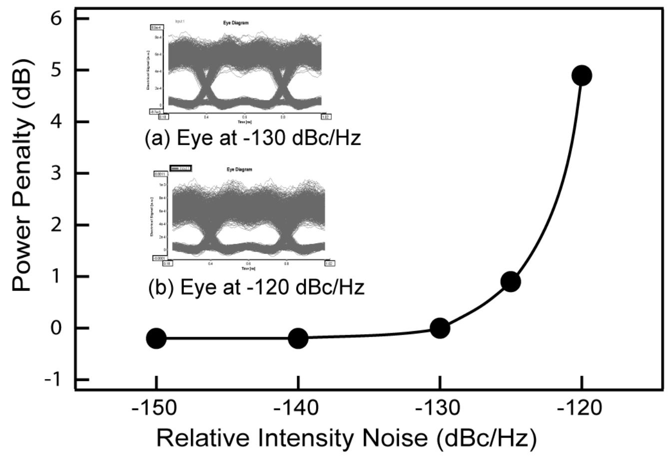

Figure 3. Power penalty for RIN variation in both the lasers

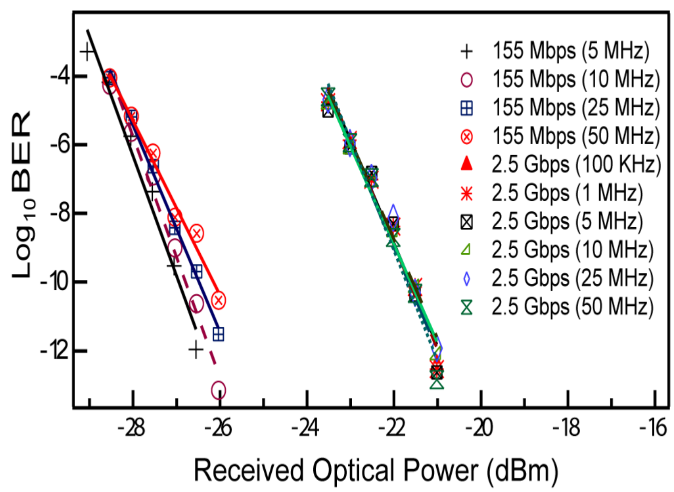

Figure 4. BER for different laser linewidths and data rates

signal-to-noise-ratio would be higher enough to transmit high quality data [9]. Thus, the homodying or self-mixing process would contribute to receive the baseband data with minimal phase noise. Low pass filtering would then is used to retrieve the transmitted data in the proposed system.

III. SIMULATION SET UP

Fig. 1 shows our proposed system, which consists of two independent DFB lasers operating at 1550 and 1550.32 nm, combined together by a 3 dB coupler. Simulation was performed using VPI Transmission maker 7.6™ platform. Linewidths of both lasers are kept 5 MHz with a RIN of -130 dBc/Hz each. The difference between the laser frequencies is maintained 40 GHz at our desired mm-wave frequency. 2.5 Gbps amplitude-shift-keyed (ASK) non-return-to-zero (NRZ) data with a pseudo-random-bit-sequence (PRBS) of $2^7 - 1$ is used to drive the Mach Zehnder modulator (MZM) with 30 dB extinction ratio. Bias voltage of the MZM was 6.5 volts. The double sideband modulated output after the MZM is then transmitted over 25 km single-mode fiber (SMF) to the PD; detected, amplified and then self-mixed or homodyned using a mixer. The fiber attenuation was 0.2 dB/km with a chromatic dispersion of 16 ps/nm.km. Responsivity of the PD was 1 A/W and the electrical amplifiers had a gain of 30 dB each. The relevant optical and RF spectra are shown in the insets of Fig. 1. Data was finally recovered using a low pass filter with a bandwidth of 5 GHz.

IV. RESULTS AND DISCUSSION

Fig. 2 shows the BER curves for the recovered signals for both back-to-back (BTB) case and after transmission over 25 km of SMF. At a BER of 10^{-9}, a negligible power penalty of 0.1 dB is observed, which can be attributed to fiber chromatic dispersion. Fig. 2 also confirms that at a fixed data rate, the sensitivity of the system degrades with the decrease of frequency separation of the lasers from 40 GHz to 10 GHz, as expected.

Phase noise effects and RIN plays an important role in microwave photonic systems as the BER penalty increases due to increased phase noise and RIN. Fig. 3 shows the power penalty versus RIN curve using different fixed RINs from -150 to -120 dBc/Hz for both the lasers and -130 dBc/Hz is the reference. Almost no power penalty is observed as the RIN is varied from -150 to -130 dBc/Hz. However, a power penalty of 4.9 dB is experienced as the RIN values are changed from -130 to -120 dBc/Hz. This is however a worst case scenario, as the commercially available DFB lasers now-a-days exhibit a RIN of less than -130 dBc/Hz.

The effects of laser linewidth were investigated in Fig. 4. It shows that, at the system data rate of 2.5 Gbps, linewidth variation of both the lasers from 100 KHz to 50 MHz has very little effect on the overall BER performance. Increased linewidth variation of the lasers translates to higher phase noise effects in a heterodyne system. Hence, it is found that the RF homodyne technique in our proposed system effectively minimized the phase noise effects as it showed minimal power penalty with the increase of linewidths of both the lasers. However, with a much lower data rate, such as 155 Mbps, a power penalty of 1 dB is observed. This power penalty is due to the reduction of phase correlation between successive data pulses for the laser linewidths being closer to the modulating data rates [10].

V. Conclusions

Our proposed system architecture exhibits negligible power penalty due to linewidth variations of both the lasers for 2.5 Gbps data transmission with a RIN of -130 dBc/Hz. Also, commercially available lasers with RIN values from -150 to -130 dBc/Hz offered good performance in terms of power penalty for our system. Hence, the proposed system offers minimal phase noise effects using the optical heterodyning of laser sources and homodyning of the detected RF signals. The scheme would therefore eliminate the need for phase/frequency locking of lasers and costly modulators and LO's/mixing circuitry. Such simplified and cost-effective implementation of mm-wave RoF system has a great potential to be competitive with other access technologies such as PON and fiber-to-the-home.

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