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Digital predistortion of 75-110 GHz W-band frequency multiplier for fiber wireless short range access systems

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Abstract: We present a W-band fiber-wireless transmission system based on a nonlinear frequency multiplier for high-speed wireless short range access applications. By implementing a baseband digital signal predistortion scheme, intensive nonlinear distortions induced in a sextuple frequency multiplier can be effectively pre-compensated. Without using costly W-band components, a transmission system with 26km fiber and 4m wireless transmission operating at 99.6GHz is experimentally validated. Adjacent-channel power ratio (ACPR) improvements for IQ-modulated vector signals are guaranteed and transmission performances for fiber and wireless channels are studied. This W-band predistortion technique is a promising candidate for applications in high capacity wireless-fiber access systems.

OCIS codes: (060.4510) Optical communications; (060.5625) Radio frequency photonics; (350.4010) Microwaves.

References and links

1. "FCC online table of frequency allocations," `www.fcc.gov/oet/spectrum/table/fcctable.pdf`.
2. C. W. Chow, F. M. Kuo, and J. W. Shi, "100 GHz ultra-wideband (UWB) fiber-to-the-antenna (FTTA) system for in-building and in-home networks," Opt. Express **18**, 473–478 (2010).
3. J. Marti and J. Capmany, "Microwave photonics and radio-over-fiber research," IEEE Microw. Mag. **10**, 96–105 (2009).
4. R. W. Ridgway, D. W. Nippa, and S. Yen, "Data transmission using differential phase-shift keying on a 92 GHz Carrier," IEEE Trans. Microwave Theory Tech. **58**, 3117–3126 (2010).
5. A. Hirata, M. Harada, and T. Nagatsuma, "120-GHz wireless link using photonic techniques for generation, modulation, and emission of millimeter-wave signals," J. Lightwave Technol. **21**, 2145–2153 (2003).
6. R. Sambaraju, J. Herrera, J. Martí, D. Zibar, A. Caballero, J. B. Jensen, I. Tafur Monroy, U. Westergren, and A. Walber, "Up to 40 Gb/s wireless signal generation and demodulation in 75-110 GHz band using photonic technique," in *2010 IEEE Topical Meeting on Microwave Photonics (MWP)*, 1–4, (2010).
7. Y. Park and J. S. Kenney, "Adaptive digital predistortion linerization of frequency multipliers," IEEE Trans. Microwave Theory Tech. **51**, 2516–2522 (2003).
8. L. C. Chang and Y. L. Lan, "Analysis of amplitude and phase predistortion and polynomial-based predistortion in OFDM systems," in *2007 6th International Conference on Proceedings of Information, Communications & Signal Processing (ICICS)*, 1–5 (2007).
9. Y. Park, R. Melville, R. C. Frye, M. Chen, and J. S. Kenney, "Dual-band transmitters using digitally predistorted frequendy multipliers for reconfigurable radios," IEEE Trans. Microwave Theory Tech. **53**, 115–122 (2004).
10. H. Chang, J. Tsai, T. Huang, H. Wang, Y. Xia, and Y. Shu, "A W-band high-power predistorted direct-conversion digital modulator for transmitter applications," IEEE Microw. Wirel. Compon. Lett. **15**, 600–602 (2005).

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1. Introduction

Driven by the increasing demand of bandwidth intensive applications, the Federal Communications Commission (FCC) has opened the commercial use of spectra in the 71-75.5GHz, 81-86GHz, and 92-100GHz bands [1], which are recommended for multi-gigabit capacity wireless access and broadband millimeter-wave (MMW) applications, e.g. uncompressed high definition video signal transmission and high speed internet, etc [2]. On the other hand, Radio-over-Fiber (RoF) technology provides elegant solutions for broadband requirements beyond gigabit thanks to ultra-wide bandwidth and agility characteristics of photonic devices [3]. Therefore, for future ultra high-speed wireless access applications, the convergence of optical fiber links with spectral resources in the W-band (75-110GHz) is highly recommended and intensively under-researched [4]. Generally, costly broadband optical/MMW components such as unitraveling-carrier photodiode, harmonic mixer and power amplifier are necessary for a W-band direct-conversion fiber-wireless transmission system [5]. For cost-efficiency consideration, it is desirable to have an alternative solution for up-converting carrier frequency to the W-band. By introducing a frequency multiplier serving as a carrier frequency translator, a frequency multiplication scheme for wireless signal transmitter is currently of great interest. A multi-fold frequency multiplication transmitter cooperating with fiber wireless transmission can avoid using ultra-broadband optoelectronic devices and poor efficiency harmonic generation approaches, which releases bandwidth requirements and improves the system power efficiency [6]. Since a frequency multiplier is highly nonlinear device, predistortion technique is usually applied to obtain correct modulation information after frequency translation [7]. By performing baseband signal transformation in the digital domain, predistortion takes into account modifications of multiplier input signals to counteract the distortion that arises from gain compression (AM-AM distortion) and phase deviation (AM-PM, PM-PM distortion). In this way, distortions of up-converted signal output from the multiplier are consequently suppressed. Digital predistortion technique has been applied to linearize the power amplifiers in modern mobile base station transmitters [8] and frequency doublers in dual-band RF front-end systems [9]. In the MMW regime, predistortion technique for up to 77GHz power amplifiers was also reported [10]. However, to the best of our knowledge, research on predistortion techniques for a W-band frequency multiplier with cooperative optical fiber transmission is still at an early stage.

In this paper, we present and demonstrate a novel predistortion technique for a W-band fiber-wireless system based on a sextuple frequency multiplier which translates a carrier frequency from K-band to W-band. The inherent nonlinearity of the frequency multiplier is characterized by pre-measurement of AM-AM and AM-PM distortions. In the digital domain, the recursive least squares (RLS) algorithm is applied to make the digital iterative loop converge to the inverse property of the multiplier distortion. In the experiment, a 99.6GHz fiber-wireless system carrying predistorted quadrature phase shift keying (QPSK) and 16-ary quadrature amplitude modulation (16-QAM) signals with 26km fiber and up to 4m wireless transmission is established. An 18.9dB and a 16.8dB adjacent-channel power ratio (ACPR) improvements for QPSK and 16-QAM signals are achieved respectively, which demonstrates the effective functionality of the predistortion approach and the applicability of the proposed predistortion scheme. To evaluate the transmission performance of the fiber-wireless system, the bit error rate (BER) performances of fiber and wireless channels are investigated for QPSK and 16-QAM signals, respectively.

2. Principle and experimental setup

The experimental setup of the W-band fiber-wireless transmission system is shown in Fig.1. A sextuple frequency multiplier (Agilent E8257DS15) serves as a frequency translator in the W-band wireless transmitter module where the carrier frequency is translated from K-band to

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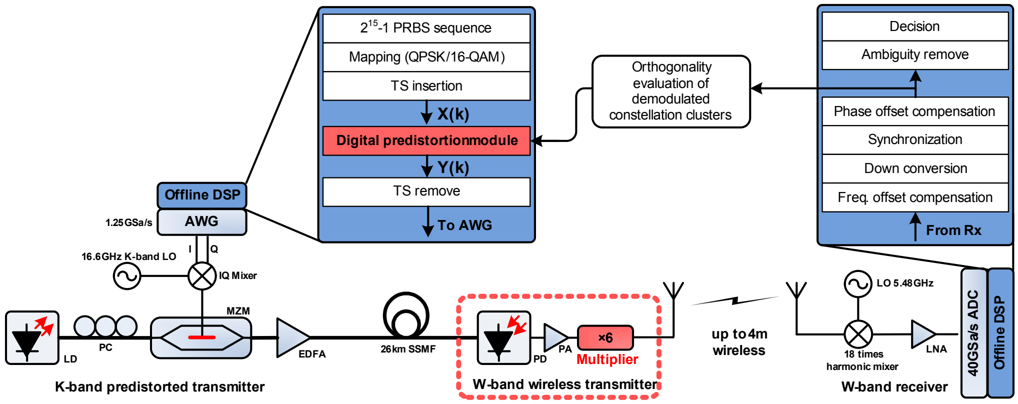

Fig. 1. Experimental setup of a digital predistorted W-band wireless access system. PC: polarization controller PA: power amplifier. LNA: Low noise amplifier.

W-band. When a modulated bandpass waveform is fed into a frequency multiplier, its output contains harmonics and intermodulation components of the desired order. The output of a n-order frequency multiplier $Y(t)$ can be expressed by

$$Y(t) = Re\{A[r(t)]e^{j\left[n\omega_0 t + n\cdot\varphi(t) + P[r(t)]\right]}\} \tag{1}$$

where $r(t)$ and $\varphi(t)$ are the amplitude and phase of the complex baseband input signal and ω_0 is the input carrier frequency. In general, the distortion arising from the frequency-multiplication process can be partly represented by polynomial functions $A[\cdot]$ and $P[\cdot]$, which are corresponding to the nonlinear AM-AM and AM-PM distortions. Another distortion applying n times of $\varphi(t)$ linear phase deviation is called PM-PM distortion. To counteract the baseband distortion, digital transformation of input complex signal needs to be implemented as an inverse model of the frequency multiplier distortion.

As shown in Fig.1, offline digital signal processing (DSP) is performed at the transmitter side of the fiber link by using MATLAB to generate predistorted baseband signals, which is stored in a 1.25GSa/s arbitrary waveform generator (AWG). In the digital domain, a data stream consisting of pseudo-random binary sequence (PRBS) with a length of $2^{15}-1$ is mapped to a symbol sequence with QPSK/16-QAM modulation format. 1000 training symbols for predistortion and another 100 symbols for synchronization are inserted at the beginning of the symbol sequence, forming the predistortion input sequence $X(k)$ of the digital predistortion module, where k is the symbol index. The structure of the digital predistortion module is presented in detail in the following paragraph. Subsequently, the 1000 train symbols are removed from the output symbol sequence $Y(k)$. After the digital to analog conversion in the AWG, the predistorted baseband waveform is mixed with a 16.6GHz K-band RF local oscillator (LO) using an IQ mixer. The output up-converted signal is modulated on an optical carrier at 1549.3nm in a Mach-Zehnder modulator (MZM), which is followed by a booster EDFA launching the optical signal into a 26km standard single mode fiber (SSMF). After fiber transmission and photodetection, the 16.6GHz RF signal is translated to a 99.6GHz W-band wireless signal in the sextuple frequency multiplier. Subsequently, the signal is radiated through an up to 4m wireless distance using a pair of W-band hone antennas. At the receiver side, the 99.6GHz signal is mixed with the 18^{th} harmonic of a 5.48GHz LO in a 18-order harmonic mixer (Agilent 11970W) to be down-converted to 960MHz. The bandwidth of the harmonic mixer is $\sim$600MHz, which is the main limitation to achieve higher data rate in our experiment. To demodulate QPSK/16-QAM

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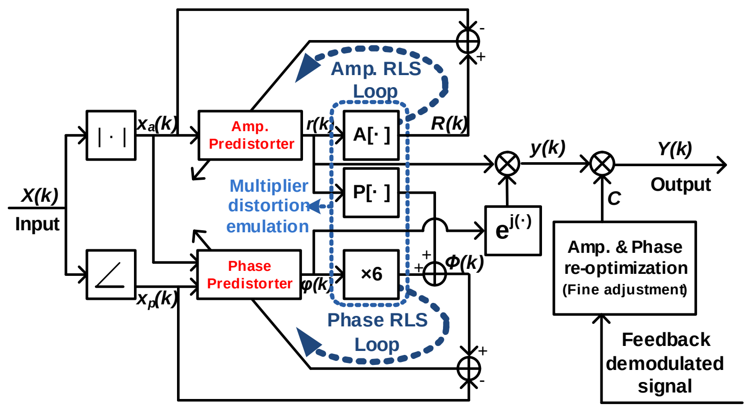

Fig. 2. Block diagram of the digital signal processing in the digital predistortion module.

data signals, the down-converted signal is digitalized with a 40GSa/s digital oscilloscope and the waveform is processed offline with applicable algorithms. In the digital domain, frequency offset compensation, digital down-conversion and synchronization are performed followed by QPSK/16-QAM phase offset compensation. The constellation of the demodulated QPSK/16-QAM baseband signal after phase offset compensation is evaluated in terms of the IQ orthogonality which is then fed into the digital predistortion module as a auxiliary guide to perform fine adjustments for the predistorted signal. Finally, the BER is obtained in the receiver by using direct error counting of 2×10^5 bits.

Since the influences of the multiplier can be represented by definite polynomial-based functions, we can extract the coefficients of $A[\cdot]$ and $P[\cdot]$ by pre-measurement of AM-AM and AM-PM distortions [7]. After characterizing $A[\cdot]$ and $P[\cdot]$, the predistortion processing can be achieved as shown in Fig.2. The digital predistortion is based on two parallel iterative loops, one of which is for amplitude distortion and the other serves for phase deviation. The first 1000 symbols of $X(k)$ are used to drive the predistorters in amplitude iterative loop and phase iterative loop. In the experiment, both amplitude predistorter and phase predistorter are 4-term polynomials so that the 8 coefficients are updated with the iterations. The RLS algorithm is applied to drive the iterative loops converge to a proper predistortion function, in other words, the inverse characteristic of the frequency multiplier. By combining the loop outputs $r(k)$ and $\varphi(k)$, a fundamental predistorted baseband symbol sequence $y(k)$ can be obtained. Subsequently, by referring the feedback constellation orthogonality information, a re-optimized complex factor C ($C\approx1$) is determined with the conventional hill-climbing algorithm. The predistorted complex baseband signal $Y(k)$ which is the product of C and $y(k)$ is obtained and output from the digital predistortion module.

3. Experimental results

To characterize the frequency multiplier, pre-measurement is firstly performed by driving the transmitter with an unmodulated 16.6GHz LO. The results show the frequency multiplier has a minimal effective input power of -2dBm due to the switching voltage of Schottky diodes in the multiplier. To avoid the turn-off and the over-saturation effects, the input signal power is clipped from -1dBm to 6dBm, which indicates a limited dynamic range for the input signal. It is also shown from the pre-measurement that the input-output conversion loss is more than 30dB in the W-band since the frequency multiplier is based on high-order nonlinear operation

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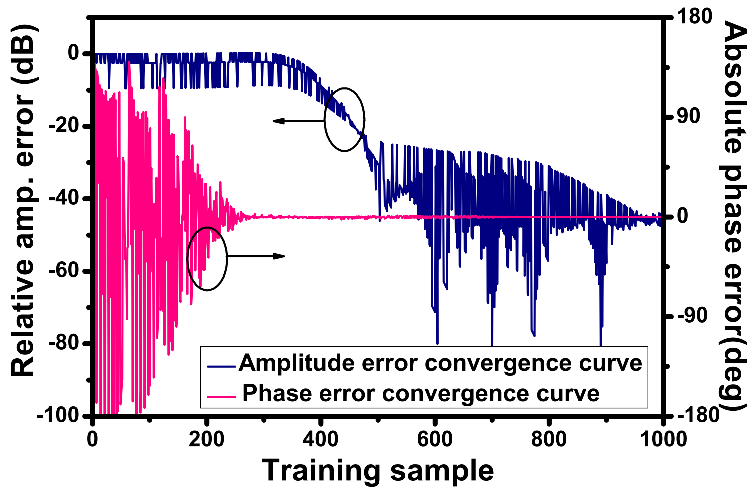

Fig. 3. RLS convergence curves for amplitude and phase predistortion loops.

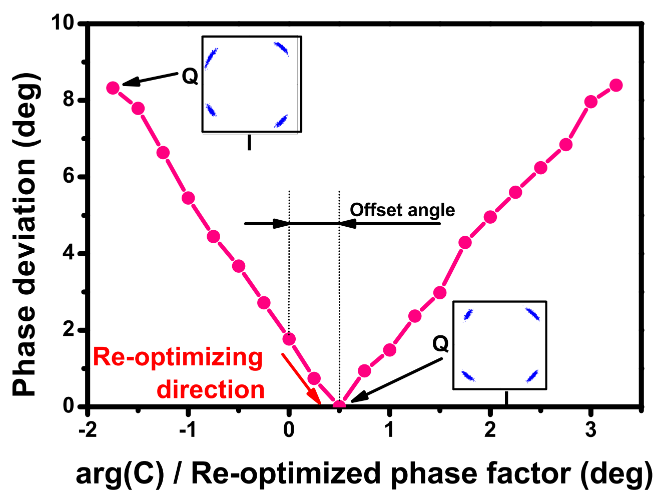

Fig. 4. Orthogonality re-optimization for the QPSK signal.

of a passive diode. For nonlinearity evaluation, AM-AM and AM-PM responses are extracted and represented in 4-term polynomials where the 6^{th}-order term dominates.

Figure 3 shows the convergence curves for the amplitude RLS loop and the phase RLS loop for 312.5Mb/s QPSK signal. The normalized amplitude error $|[R(k)-x_a(k)]/x_a(k)|$ drops by 40dB and the absolute phase error $|\phi(k)-x_p(k)|$ is less than 0.02° after 1000 iterations, which verifies the feasibility of the RLS algorithm for digital predistortion. To accelerate convergence, the parameters of the RLS algorithm need to be further optimized. Due to the pre-measurement error and time-dependent variance of the frequency multiplier, fine adjustment of baseband symbols is performed based on the physical feedback path to further guarantee the predistortion performance. Figure 4 shows the angle deviation from 90° of the demodulated QPSK

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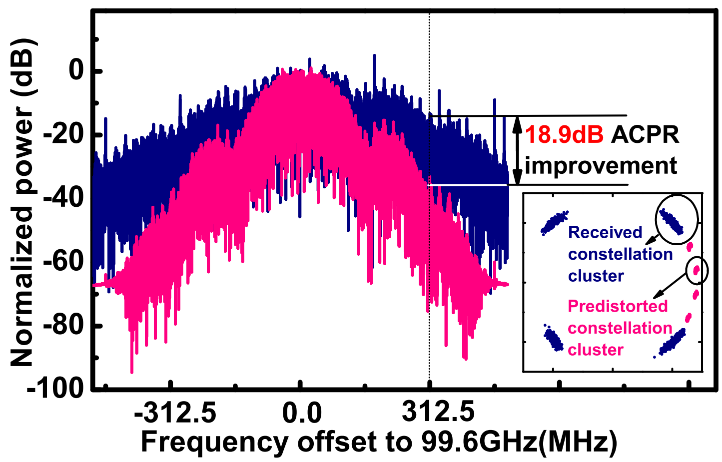

Fig. 5. QPSK spectra with (red) and without (blue) predistortion. **Inset:** Predistorted (red) and received (blue) QPSK constellations.

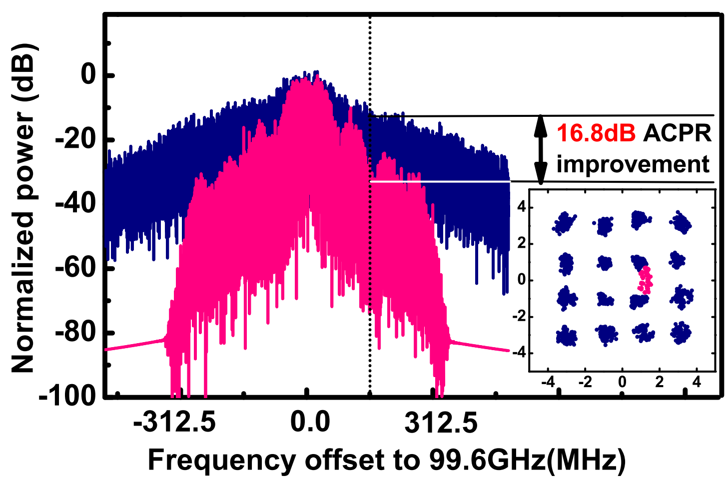

Fig. 6. 16-QAM spectra with (red) and without (blue) predistortion. **Inset:** Predistorted (red) and received (blue) 16-QAM constellations.

constellation as a function of the complex angle of the re-optimized factor C for 3dBm input power. It can be seen a 0.5° angle offset from the fundamental predistorted sequence $y(k)$ is induced to achieve optimized orthogonality, which also implies the fine adjustment is able to give an up to 2° orthogonality correction.

The inset of Fig.5 shows the constellations of the demodulated 312.5Mb/s QPSK and the predistorted symbol sequence $Y(k)$ in the digital predistortion module. For the received QPSK constellation, it qualitatively shows a good magnitude uniformity and angle orthogonality, which implies the effectiveness of the digital predistortion for the sextuple frequency multiplier. The

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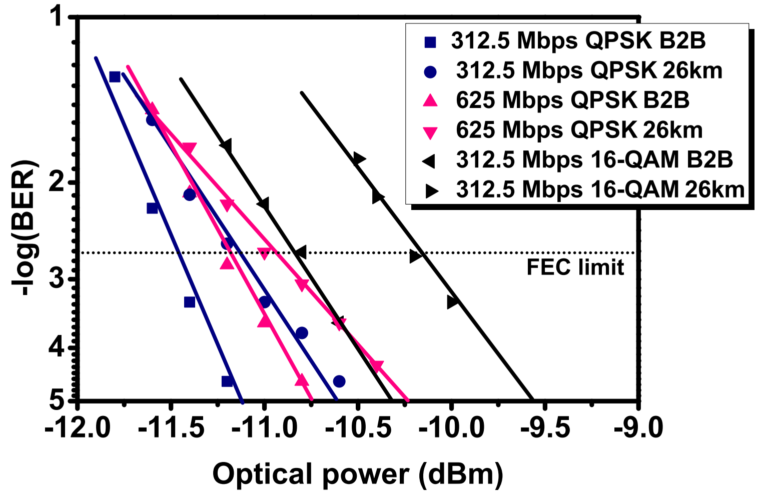

Fig. 7. Fiber transmission performances for the 99.6GHz fiber-wireless transmission system. BER vs optical power before the PD with fixed 1m wireless distance.FEC: forward error correction.

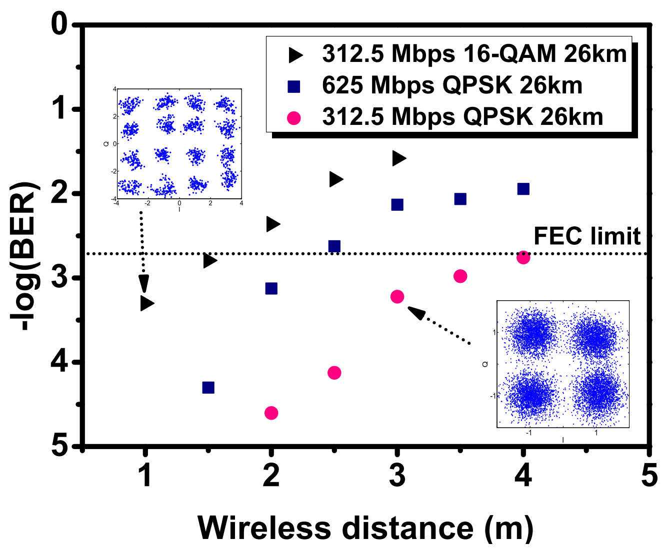

Fig. 8. Wireless transmission performances for the 99.6GHz fiber-wireless transmission system. BER vs 99.6GHz wireless transmission distance with fixed 26km fiber transmission. **Inset:** demodulated constellation of QPSK and 16-QAM signals.

constellation of $Y(k)$ shows that the predistorted clusters are confined in a limited area which implies the inverse nonlinear characteristic of the frequency multiplier. Figure 5 shows the measured 312.5Mb/s QPSK spectra output from the transmitter with and without digital predistortion processing. It can be seen that without the predistortion, the signal is spread over 500MHz and it is impossible to be demodulated due to intermodulation distortions. With the digital predistortion, the ACPR quantitatively performs an 18.9dB improvement at 312.5MHz offset from the center frequency. For the 312.5Mb/s 16-QAM signal, the constellations of the demodulated signal and the predistorted sequence for 3dBm input power as well as the spec-

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tra with and without predistortion are shown in Fig.6. An ACPR improvement of 16.8dB at 156.25MHz offset is also observed, which verifies the predistortion scheme is applicable for different modulation formats. After predistortion, some residual 6^{th}-order intermodulation distortion still exists and we expect this residual distortion can be further suppressed by treating more terms in the polynomial predistorters.

The measured BER curves against the optical power before PD for fixed 1m wireless transmission distance are shown in Fig.7. For QPSK modulation format, there is a ∼0.3dB negligible power penalty after 26km fiber transmission with respect to the B2B case at a BER of 2×10^{-3} (FEC limit), and another 0.3dB power penalty appears when increasing the data rate from 312.5Mb/s to 625Mb/s due to the bandwidth limitation of the harmonic mixer. For 16-QAM modulation format, the data rate is fixed at 312.5Mb/s. The B2B transmission performs a ∼0.6dB power penalty with respect to the QPSK case. In the 16-QAM case, error bits mainly come from wrong decision between the largest power level (outer 4 clusters) and the secondary power level (middle 8 clusters) due to the nonlinear compression affects high power symbols dominantly, which results in a degraded signal-to-noise ratio (SNR) for outer constellation clusters. After 26km fiber transmission, ∼0.6dB transmission power penalty is observed with respect to the B2B case, which implies the 16.6GHz predistorted 16-QAM signal is more sensitive to fiber dispersion than uniform power level QPSK signal. Figure 8 shows the BER curves versus the wireless transmission distance while the optical power after fiber transmission is fixed at -10dBm. To keep the BER below the 2×10^{-3} threshold, the maximal wireless distances for 312.5Mb/s QPSK, 625Mb/s QPSK and 312.5Mb/s 16-QAM signals are 4m, 2.5m and 1.5m, respectively. It can be seen that due to the intensive path loss, this proof-of-concept experiment supports 4m wireless transmission distance, which is much shorter than the reach of current wireless systems. A quantitative experiment for characterizing the W-band wireless path loss shows 33dB wireless link loss for 4m transmission, which implies that the W-band wireless transmission system is more suitable for short range or indoor access systems.

4. Conclusions

This paper has presented a W-band fiber-wireless system that employs digital predistortion technique for eliminating nonlinear distortions in a frequency multiplier. We experimentally proved the feasibility of the predistortion processing in the digital domain. Without need for costly high-frequency optical or MMW components such as W-band photodiode or power amplifier, 312.5Mb/s QPSK and 16-QAM signals carried by 99.6GHz MMW were obtained with detailed transmission performance discussions. 18.9dB and 16.8dB ACPR improvements for QPSK and 16-QAM signals confirmed the capability of the proposed predistortion scheme to counteract nonlinear distortions, which makes the system as a good candidate for future indoor W-band wireless applications.

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