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Overcoming Modal Bandwidth Limitation in Radio-over-Multimode Fiber Links

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Abstract—Employing the optical frequency multiplication method, the theoretical modal bandwidth limitation of multimode fiber (MMF) can be overcome in radio-over-fiber links. The principle is analyzed theoretically and supported experimentally by generation and transmission of microwave carriers up to 40 GHz and 16- and 64-level quadrature-amplitude-modulated (QAM) radio signals in the 24- to 30-GHz band over 4.4-km MMF link.

Index Terms—Multimode fiber (MMF), optical fiber communication, radio-over-fiber (RoF), wireless access networks.

I. INTRODUCTION

THE USE of multimode fiber (MMF) for the last mile access networks has attracted much attention in the last years due to the MMF's dominant position in already installed fiber infrastructure inside buildings. Research efforts have been mainly dedicated to enhance baseband digital transmission performance of MMF links [1], as well as to develop low-cost radio-over-fiber (RoF) techniques for short MMF distances [2]. For the emerging broadband wireless systems operating at carrier frequencies in the microwave/millimeter wave bands, the theoretical modal bandwidth limit imposed by the well-known bandwidth-distance product, confines the use of MMF to very short links. Exploiting the passband transmission region of MMF, microwave signals can be transmitted over MMF links [3], but the passband region differs with fiber length variations, which might not be practical in the rollout of a radio-over-MMF-based infrastructure. Another method to overcome this theoretical bandwidth limitation is the optical frequency multiplication (OFM) principle [4]. Preliminary experiments have demonstrated the remote delivery of microwave signals up to 18 GHz over an MMF link [5]. However, to our best knowledge, the fact of surpassing this theoretical modal bandwidth has not been explained accurately yet. In this letter, we investigate the OFM principle and its application to MMF transmission with some theoretical models. In addition, we present the results of an experimental analysis of the OFM performance for the generation of microwave carriers up to 40 GHz and their transmission over an MMF link. Up-conversion and transmission of M-ary quadrature-amplitude-modulated (M-QAM) radio signals in the 24- to 30-GHz band is also demonstrated and compliant with the requirements of wireless standard IEEE 802.11a.

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Fig. 1. OFM principle.

II. THEORY

A. OFM Principle

OFM is based on harmonics generation by frequency modulation to intensity modulation (FM-IM) conversion through a periodic bandpass filter. The frequency modulation of a light source ω_0 by a sinusoid signal of sweep frequency ω_{sw} can be represented by

$$E_{in}(t) = E_0 \cdot e^{j(\omega_0 t + \beta \sin(\omega_{sw} t) + \phi(t))} \quad (1)$$

where β indicates the frequency modulation index and E_0 is the amplitude of the optical field.

When a Mach-Zehnder interferometer (MZI) with impulse response $h_{MZI}(t) = 1/2[\delta(t) + \delta(t - \tau)]$ is used as a periodic bandpass filter, and the resulting signal is launched into a photodiode [Fig. 1(a)], the intensity of the electrical signal obtained can be expressed as

$$i(t) = \frac{1}{2} |E_0|^2 \cdot [1 + \cos(\omega_0 \tau + \beta \sin(\omega_{sw} t) - \beta \sin(\omega_{sw}(t - \tau)) + \dot{\phi} \tau)] \quad (2)$$

with $\dot{\phi} \tau = \phi(t) - \phi(t - \tau)$, where τ is the time delay in one of the arms of the MZI, and $\dot{\phi}$ indicates the laser phase noise contribution. Expanding (2) with Bessel functions of the first kind (J_n), it can be seen that the signal at the output of the photodiode has frequency components at every harmonic $n \cdot \omega_{sw}$ of the sweep frequency, with relative amplitudes

$$\left. \begin{aligned} &\cos((\omega_0 + \dot{\phi})\tau) \cdot J_{2n}(2\beta \sin(\frac{\omega_{sw}\tau}{2})), (\text{even}) \\ &\sin((\omega_0 + \dot{\phi})\tau) \cdot J_{2n-1}(2\beta \sin(\frac{\omega_{sw}\tau}{2})), (\text{odd}) \end{aligned} \right\} \quad (3)$$

for the even and the odd harmonics, respectively, and that the laser phase noise impact can be considered negligible as long as $\dot{\phi} \ll \pi/2\tau$ [4].

B. MMF Model and Total System Response

According to [6], the response $h_{\text{MMF}}(z, t)$ of an MMF at a position z to an impulse launched at $z = 0$ can be modeled as

$$h_{\text{MMF}}(z, t) = \sum_k \omega_k \cdot e^{(-\gamma_k z)} \cdot \delta(t - \tau_k z) \quad (4)$$

where the set ω_k is the mode power distribution (MPD), γ_k is the attenuation coefficient for mode k , and τ_k is the mode group delay (MGD) per-unit length. The corresponding transfer function is periodic against frequency, and its shape compresses with long fiber lengths and expands with short fiber lengths. This characteristic determines the well-known bandwidth-distance product ($\text{BW} \cdot L$), which theoretically limits the MMF bandwidth for baseband transmission to the first -3-dB fall.

In an OFM link, where the light source is frequency swept by ω_{sw} , the theoretical $\text{BW} \cdot L$ product is not applicable like in baseband transmission links with continuous-wave light sources. Instead, the complete MMF frequency response in (4) has to be considered in combination with the MZI. As a result, the FM-IM conversion is performed through a total periodic filter determined by $h_{\text{SYST}}(z, t) = h_{\text{MZI}}(t) * h_{\text{MMF}}(z, t)$ [Fig. 1(b)]. The transfer function $H_{\text{SYST}}(z, f)$ of such a total filter is depicted in Fig. 2(d). In this example, the MZI shift delay is $\tau = 100$ ps [Fig. 2(a)] and the MMF is modeled with the values of MPD and MGD indicated in Fig. 2(b) [6] (example for illustration purposes), which yield the MMF transfer function $H_{\text{MMF}}(z, f)$ depicted in Fig. 2(c) for $z = 4$ km (attenuation is not included). As can be seen, the shape of the total periodic filter is mainly dictated by the MZI response, whereas the MMF introduces some ripple-patterns inside the dominating MZI lobes. In a real link, mode mixing between mode groups may occur due to transmission and connector offset. Each mode group output yields a combination of weighted versions of the input signal with corresponding path delay. As a result, the FM-IM conversion is performed in two steps: first, through the MZI (with τ), and second, through the MMF link (with multiple τ_i combinations per mode group). Thus, the desired harmonic band can be optimized through the MMF with the parameters ω_0 , τ , and β , which may help to alleviate the dramatic effect of dips in the (conventional) MMF frequency response.

III. EXPERIMENTAL MEASUREMENTS

To test the effects of MMF transmission in an RoF link based on OFM, an experimental arrangement according to the schematics in Fig. 1 was setup. A phase modulator was used to modulate the frequency of a continuous-wave laser source (1310 nm) by a sweep frequency f_{sw} . The free-spectral range of the MZI was 10 GHz ($\tau = 100$ ps) and the photodiode had a 25-GHz -3-dB bandwidth. The fiber employed in the transmission was a 4.4-km-long 50- μm -core graded-index MMF with $1.604\text{-GHz} \cdot \text{km}$ $\text{BW} \cdot L$ product and 0.49-dB/km attenuation at 1310 nm. The output of the photodiode was boosted with a 40-GHz broadband amplifier and visualized with a vector signal analyzer.

Fig. 3(a) shows the harmonic strength obtained after MMF transmission at the RF frequency multiples of f_{sw} , with f_{sw} varying from 1 to 6 GHz. As indicated in (3), the relative amplitude of each harmonic depends on f_{sw} , τ , and β ; thus, as-

Fig. 2. System transfer functions: (a) MZI transfer function $|H_{\text{MZI}}(f)|$ with $\tau = 100$ ps; (b) MMF characterization example (MPD and MGD); (c) MMF transfer function $|H_{\text{MMF}}(z = 4 \text{ km}; f)|$ corresponding to characteristics in (b); (d) total transfer function $|H_{\text{SYST}}(z = 4 \text{ km}; f)|$.

suming a fixed τ (MZI), f_{sw} and β can be selected to optimize performance at the desired band. Fig. 3(b) shows the RF spectra measured at the output of the photodiode with $f_{\text{sw}} = 6$ GHz. Comparing the measured spectra in the back-to-back case and after the MMF link, the envelope of the harmonics amplitude is preserved, and only slight fluctuations in the harmonic distribution power can be observed.

To evaluate the link performance for radio signals transmission and upconversion, the optical FM signal (with $f_{\text{sw}} = 6$ GHz) was intensity modulated (externally) by 16-QAM and 64-QAM signals at 300 MHz, with symbol rates (SRs) ranging from 5 to 20 MS/s and error vector magnitude (EVM) values ranging from 0.5% to 1.8% (i.e., signal-to-noise ratio (SNR) from 46 to 34.9 dB). Then, the RF signals obtained along with the fourth harmonic ($f_{4\text{th}} = 24$ GHz) at $f_{\text{RF}} = 23.7$ GHz, and with the fifth harmonic ($f_{5\text{th}} = 30$ GHz) at $f_{\text{RF}} = 29.7$ GHz, were selected for evaluation.

The SNR of the selected signals was derived from EVM measurements, in order to calculate the SNR degradation introduced by the RoF analog link. Fig. 4 shows the total SNR penalty expe-

Fig. 3. Harmonics generation by OFM: (a) Harmonics strength with varying sweep frequency (sw); (b) spectra measurements with $f_{sw} = 6$ GHz, back-to-back (left) and after 4.4-km MMF transmission (right).

Fig. 4. SNR penalty experienced by the 16-QAM and 64-QAM signals recovered at 23.7 and 29.7 GHz due to OFM upconversion (OFM) and MMF transmission (MMF).

rienced by the 16-QAM and 64-QAM signals recovered at 23.7 and 29.7 GHz, indicating the penalty contribution due to OFM upconversion with respect to the input signals at 300 MHz and due to MMF transmission, separately. The SNR penalty margin to comply with the IEEE802.11a standard specification for the transmitter constellation error (i.e., 5.6% and 7.9% for 64-QAM with code rate 3/4 and 2/3, respectively; and 11.2% for 16-QAM with code rate 3/4) is also indicated with error bars.

The SNR degradation due to OFM upconversion does not depend on the QAM constellation, but on the signal bandwidth SR. The lower OFM upconversion SNR penalty observed with higher SR occurs because the *effective* modulation index of the intensity modulator varies with SR and the phase noise contribution, which is higher for higher SR in the input signals, and

does not scale linearly in terms of SNR penalty. However, the SNR penalty margin is still narrower for higher SR because the input signals at 300 MHz also had worse SNR for higher SR. The SNR penalty caused by MMF transmission was ~ 2.4 and ~ 4.5 dB for the signals recovered at 23.7 and 29.7 GHz, respectively. The different performance observed for the signals at 23.7 and 29.7 GHz has three main penalty sources: first, the average power distributed to the fourth and the fifth harmonics is different; second, the fifth harmonic (30 GHz) lies 5 GHz beyond the nominal photodiode bandwidth, thus, the photodiode response at 29.7 GHz is less efficient; and third, the 40-GHz broadband amplifier employed in the experiment produced a noise peak in the band around 30 GHz [see noise profile in Fig. 3(b)], which introduced additional distortion in the signals recovered in this band.

As can be seen in Fig. 4, the 16-QAM signals meet the standard requirements in all cases. For 64-QAM, a maximum of 10 MS/s at 29.7 GHz could be successfully transmitted according to the more strict requirements (though the back-to-back upconversion was successful in all the cases). In order to comply with the standard specification for the 20-MS/s 64-QAM signals at 29.7 GHz, the input signals at 300 MHz should have an SNR better than 40 and 37 dB for 3/4 and 2/3 code rates, respectively.

IV. CONCLUSION

In this letter, we have demonstrated how, by employing the OFM technique, the modal bandwidth limitation of an MMF link can be overcome in RoF systems. The experiments reported here show that OFM can be applied to generate microwave carriers up to 40 GHz and distribute them over 4.4 km of MMF link. Also, 16-QAM and 64-QAM radio signals are upconverted from 300 MHz to 23.7 GHz and 29.7 GHz, and recovered successfully after the MMF link. Results suggest that the system performance is not jeopardized by modal dispersion, and that any length of MMF could be used, provided that the power budget is properly dimensioned. Thus, the RF bandwidth limit of the link is determined by the distance between generated harmonics, i.e., the sweep frequency, which is an adjustable system parameter.

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