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Transmission of Microwave Signals beyond the Modal Bandwidth of Multimode Fiber Links

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Abstract — Employing the optical frequency multiplication method, we present an experimental performance analysis of the generation of microwave carriers up to 40GHz and their transmission over a 4.4km multimode fiber link. Also, 16QAM and 64QAM radio signals up to 20MS/s symbol rate are recovered successfully in the 24-30GHz band after 4.4km multimode fiber transmission, complying with the transmitter constellation error requirements of wireless standard IEEE 802.11a.

Index Terms — Optical fiber communication, wireless access networks, radio-over-fiber, multimode fiber

I. INTRODUCTION

In the last years, the use of multimode fiber (MMF) for the last mile access networks has attracted much attention 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][4], whose modal bandwidth imposes an upper limit on the achievable transmission speed and link distance. In the access network scenario, broadband wireless services are undoubtedly a prominent player, and radio over multimode fiber based distribution antenna systems makes possible a potentially cost-effective roll-out of wireless access infrastructure and its convergence with fiber-based access networks.

For wireless systems operating at carrier frequencies below 5GHz, direct modulation of a continuous wave laser diode with the radio frequency signal is the most common method to reduce cost and complexity, rather than external modulation, and the successful transmission of these signals over short MMF links has been demonstrated [5]. Emerging broadband wireless systems target operation at carrier frequencies in the microwave and the millimeter wave regions, which, apparently, confine the use of MMF to ridiculously short links (even for access distances), according to the well-known bandwidth-distance product. In spite of this theoretical limit, experiments have demonstrated that it is possible to transmit radio signals at carrier frequencies that surpass more than 20 times the theoretical bandwidth, by means of exploiting the passband transmission region of MMF [6].

However, relying on this passband region may bring about other practical complications in the roll-out of a radio over multimode fiber based infrastructure, since the passband region may differ with fiber length variations.

Another method to remotely deliver microwave signals beyond the modal bandwidth of MMF links is the optical frequency multiplication (OFM) principle [7]. OFM is based in the harmonics generation by frequency modulation to intensity modulation (FM-IM) conversion through a periodic bandpass filter, like, e.g., a Mach-Zehnder interferometer. The impulse response of a MMF, consisting of a series of delta functions corresponding to the arrival times of the individual fiber modes, can be modeled as a second interferometric stage after the periodic bandpass filter, which enhances the FM-IM conversion, reducing in turn the frequency response dependency on link length. Additionally, this method allows the up-conversion of radio signals generated at low frequencies to high microwave carriers, which further simplifies the system.

In this paper, we present an experimental analysis of the OFM performance for the generation of microwave carriers up to 40 GHz and their transmission over a MMF link. M-QAM radio signals transmission in the 24-30 GHz band is also demonstrated and compliant with the requirements of wireless standard IEEE 802.11a.

III. EXPERIMENTAL SETUP AND MEASUREMENTS

A schematic of the experimental setup is depicted in Fig. 1. A continuous wave laser source (1310nm) is frequency modulated (FM) by a sweep frequency \( f_{sw} \) with a phase modulator (PM). The radio data signal (16QAM or 64QAM at different symbol rates) on a low frequency subcarrier \( f_{sc} = 300MHz \) modulates the intensity of the optical FM with a chirp free Mach-Zehnder intensity modulator (IM). The resulting optical signal is passed through a Mach-Zehnder interferometer (MZI) with 10GHz free spectral range (FSR) and launched into a 4.4km of 50µm-core MMF link with 1.604GHz/km bandwidth-distance product and 0.49dB/km attenuation at 1310nm. After the MMF link, the signal is recovered by a 25GHz bandwidth
photodiode with 50μm fiber pigtail, pre-amplified with a 40GHz broadband amplifier and sent to a vector signal analyzer (VSA) for evaluation.

![Fig. 1: Schematic of the experimental setup (PM: phase modulator, IM: intensity modulator, MZI: Mach-Zehnder interferometer, MMF: multimode fiber, VSA: vector signal analyzer)](image)

A. Harmonic Strength Measurements

To study the OFM principle performance through the MMF transmission, a series of measurements was carried out for different sweep frequencies $f_{sw}$ applied to the phase modulator, in absence of (data) intensity modulation. Fig. 2 shows the spectra measured in a back-to-back arrangement (B2B) and after transmission over the 4.4km of MMF link, for $f_{sw} = 2$, 4, and 6GHz. The number of harmonics generated at the output of the photodiode, i.e. the multiplication factor, depends on the optical spectrum broadening produced by the optical FM, which is related to the frequency modulation index $\beta$ according to

$$f_{\Delta} = \beta \cdot f_{sw},$$

where $f_{\Delta}$ is the optical frequency deviation produced. The index $\beta$ was set to the maximum allowed by the phase modulator employed in the experiment. As can be seen in Fig. 2, more than 10 harmonics are generated with $f_{sw} = 2$GHz ($\geq 20$GHz). With $f_{sw} = 4$GHz and 6GHz, harmonics up to 40GHz (maximum bandwidth of the spectrum analyzer) could be observed, even though the -3dB bandwidth of the photodiode was 25GHz.

Comparing the measured spectra in the back-to-back case and after the MMF link, the envelope of the harmonics amplitude is preserved, and slight fluctuations can be hardly observed.

![Fig. 2: Spectra measurements with sweep frequencies (sw) 2, 4 and 6GHz; back-to-back (B2B, left) and after transmission over 4.4km of multimode fiber (MMF, right)](image)
B. M-QAM Signals Transmission Measurements

When the optical FM signal is intensity modulated by a radio signal at a low frequency subcarrier $f_{sc}$, this is obtained up-converted double sided along with all the generated harmonics of $f_{sc}$ to $f_{RF} = n f_{sc} ± f_{sc}$ (where $n$ is the $n^{th}$ harmonic) at the photodiode output. In the experiment we report here, $f_{sc}$ was set to 6GHz, and the optical FM signal was intensity modulated by 16QAM and 64QAM signals at $f_{sc} = 300$MHz, with symbol rates ranging from 5MS/s to 20MS/s. Then, the RF signals obtained along with the 4th harmonic ($f_{4th} = 24$GHz, within the photodiode -3dB bandwidth) at $f_{RF} = 23.7$GHz, and with the 5th harmonic ($f_{5th} = 30$GHz, beyond the photodiode -3dB bandwidth) at $f_{RF} = 29.7$GHz, respectively, were selected for evaluation.

To assess the quality of the QAM radio signals obtained at 23.7GHz and 29.7GHz, the error vector magnitude (EVM) was measured and compared with the maximum transmitter constellation error specification of standard IEEE802.11a for wireless signals in the 5GHz band (i.e., 5.6% and 7.9% for 64QAM with code rate 3/4 and 2/3, respectively; and 11.2% for 16QAM with code rate 3/4). The measured EVM values of the recovered QAM signals at $f_{sc} = 23.7$GHz and $f_{sc} = 29.7$GHz are depicted in Fig. 3 against the symbol rate for the back-to-back system (B2B) and after transmission over 4.4km of MMF, and compared with the EVM values of the input signals at $f_{sc} = 300$MHz from the vector signal generator (VSG). As can be seen in the figure, EVM does not depend on the modulation format, but on the signal bandwidth (symbol rate), which increases from 0.5% to 1.8% for 5MS/s to 20MS/s, respectively, for the input signals. In the back-to-back case, the recovered 20MS/s 64QAM signal at 23.7GHz experiences an EVM value of 4.6%, which implies a signal-to-noise ratio (SNR) degradation of ~8dB due to the OFM up-conversion with respect to the input signal at 300MHz. After the MMF link, the measured EVM value is 6.1%, which adds an extra SNR penalty of 2.4dB due to transmission.

For the 20MS/s 64QAM signal recovered at 29.7GHz, the measured EVM value was 5.78% in the back-to-back case, which corresponds to a SNR degradation of ~10dB due to the OFM up-conversion. This 2dB difference between the signals recovered at 23.7GHz and at 29.7GHz has three main penalty sources: first, the average power distributed to the 4th and the 5th harmonics is different (see Fig. 2); second, the 5th harmonic (30GHz) lies 5GHz beyond the nominal photodiode bandwidth, thus, the photodiode response at 29.7GHz is less efficient; and third, the 40GHz broadband amplifier employed in the experiment produced a noise peak in the band around 30GHz (as can be observed in the noise profile of all the spectra graphs in Fig. 2), which introduced additional distortion in the signals recovered in this band.

After the 4.4km MMF transmission link, the 20MS/s 64QAM signals recovered at 29.7GHz did not meet the standard recommendations, and therefore, the measured EVM values are not plotted in the graph. A maximum symbol rate of 10MS/s was transmitted successfully according with the specifications for 64QAM. On the other hand, the less strict recommendations for 16QAM signals allow their successful transmission over the MMF link even with 20MS/s. The EVM value measured for the 20MS/s 16QAM signal recovered at 29.7GHz was 9.7%, which means an additional SNR penalty of ~4.5dB due to MMF transmission.

![Fig. 3: EVM measurements of 16QAM and 64QAM radio signals: input signals at 300MHz, back-to-back (B2B) and after MMF transmission at 23.7GHz (top) and at 29.7GHz (bottom).](image-url)
23.7GHz with 20MS/s and at 29.7GHz up to 10MS/s. Hence, the maximum net throughput that can be delivered by this link complying with the standard recommendations is 80Mb/s at 23.7GHz (20MS/s 64QAM with 2/3 code rate) and 60Mb/s at 29.7GHz (20MS/s 16QAM with 3/4 code rate).

VI. CONCLUSIONS

We have demonstrated how the optical frequency multiplication principle can be applied to generate microwave carriers up to 40GHz and distribute them over 4.4 km of MMF link. Also, 16QAM and 64QAM radio signals at carrier frequencies 23.7GHz and 29.7GHz are recovered successfully (according to the transmitter constellation error recommendations of wireless standard IEEE 802.11a) after the 4.4km of MMF link, surpassing in this way the theoretical modal bandwidth of the MMF used in the experiment by more than 65 and 80 times, respectively.

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.

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