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Generation and transmission of high frequency radio signals through fiber links up to 125 km by means of the Optical Frequency Multiplication technique.

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Abstract— The transmission of 64 QAM radio data signals with a data rate up to 150Mb/s through long single mode fiber links at different frequencies has been experimentally evaluated. The system under study uses the optical frequency multiplication technique for the generation of carriers in the microwave and millimeter-wave bands. Transmission using frequencies of 18.7GHz, 19.5GHz, 19.7GHz and 29GHz is demonstrated for fiber links up to 125km, and up to 100km for transmission frequencies of 32.5GHz and 36.9GHz. A careful adjustment of the filter characteristics is crucial to fulfill the performance requirements.

I. INTRODUCTION

The increase of subscribers in wireless access networks in the oncoming years drives the need for new infrastructures, supporting the large amount of data traffic expected. Enhancing the capacity of wireless communications can be achieved by means of deploying smaller radio cells as well as carrying the information at higher carrier frequencies. Both approaches impose considerable costs in the infrastructure which may be reduced using Radio over Fiber technologies (RoF). In such systems, the radio signals at high frequencies are generated at a single remote central station and distributed to several simplified base station antennas using the optical fiber as physical link [1]. Here, the Optical Frequency Multiplication (OFM) technique is considered for the generation of the microwave and millimeter-wave frequencies at the remote central station. This technique allows the generation of radio frequencies (RF) from a local oscillator with a lower frequency (typically less than 10GHz), and its transmission through long fiber links, partially overcoming the dispersion of the link for both single-mode fiber (SMF) [2][3] and multi-mode fiber [4].

In this paper we present experimental results of the generation and transmission by means of OFM technique for different microwave and millimeter-wave frequencies through standard SMF links. The data format transmitted is 64-QAM, and signals at 18.7GHz, 19.5GHz, 19.7GHz, 29GHz, 32.5GHz and 36.9GHz have been generated. The maximum transmission distances were determined considering minimum requirements for 64QAM radio data signals with code rate 3/4 and code rate 2/3, as stated in the IEEE 802.11a standard, where the limit error vector magnitude values (EVM) are EVM1=5.623% and EVM2=7.943% respectively. The optical carrier was chosen to be around 1550nm where maximum dispersion is observed for SMF. Moreover the use of wavelengths in the 1.55μm windows allows the compatibility of the OFM system with the actual PON technology [5].

II. OFM PRINCIPLE

The OFM technique produces the mixing and frequency up-conversion of a data signal and a local oscillator at relatively low frequencies to a higher microwave or millimeter-wave frequency, by means of Frequency Modulation to Intensity Modulation (FM-IM) conversion in a periodical optical bandpass filter by which harmonic frequencies are generated. In the proposed method, a light source at a central wavelength (ω₀) is frequency modulated by a sweep frequency (f₁) obtaining a set of harmonics with a spectral separation of f₁. Afterwards a FM-IM conversion is produced using a periodic filtering of the desired harmonics. After photodetection, the frequency up-conversion product may be observed –see Figure 1. Moreover due to the chromatic dispersion of the link, the FM-IM conversion effect may be further enhanced [3].

The signal after the frequency modulation can be expressed as follows:
The proposed setup for our experiment is depicted in Figure 2; a tunable DFB laser source at 1550nm with an optical power of 2.5dBm was frequency modulated with a sweep frequency using a phase modulator. In the experiments three different sweep frequencies were used: f_swe1=6.4GHz, f_swe2=9.1GHz and f_swe3=9.5GHz. Afterwards, the signal was intensity modulated with a 64QAM radio data signal (data rate of 150Mb/s) at a low frequency subcarrier f_sc=500MHz. The intensity modulator was biased with V_{bias} to maximize the amplitude of the received signals. The modulated optical signal was then amplified by means of an Erbium Doped Fiber Amplifier (EDFA), optically filtered to reduce the ASE noise, and filtered once again by the MZI to perform the FM-IM conversion before its transmission through the standard SMF link. For the experimental demonstration, two different MZIs were used: the first one with a FSR1=20GHz and insertion loss of 14dB, and the second one with a FSR2=40GHz and insertion loss of 12dB.

In both cases, the considered transmission distances ranged from 0km up to 125km. The scheme for distances up to 50km is shown in Figure 2-setup 1, using a second EDFA before the reception block, whereas Figure 2-setup 2 shows the setup for lengths up to 125km, where the second EDFA is placed after a first span of 50km and before a second one with lengths up to 75km. A variable optical attenuator (VOA) was used before the photodetector in order to keep a constant received power of 0dBm. After the 38GHz bandwidth photodetector and an electrical amplification stage, the radio data signal was demodulated and analyzed in the vector signal analyzer (VSA).

### IV. RESULTS AND DISCUSSION

In the experimental demonstration, the 64QAM radio data signal with a bit rate of 150Mb/s was up-converted to several frequencies in different combinations of sweeping frequencies and harmonic orders: 19.7 GHz and 32.5GHz (3rd and 5th harmonic respectively obtained from f_{swe1}, 18.7GHz and 36.9GHz (2nd and 4th harmonic respectively obtained from f_{swe2}, 19.5GHz and 29GHz (2nd and 3rd harmonic respectively obtained from f_{swe3}).

\[ E_{in}(t) = E_0 e^{j[\omega_0 t + \beta \sin(\omega_0 t)]} \]  

(1)

whereas the received signal after photodetection can be written as [6]:

\[ I_{rx}(t) = \frac{1}{2} |E_0|^2 \left[ 1 + \cos(\omega_0 t) \left\{ J_1(z) + 2 \sum_{i=1}^\infty (-1)^i J_{2i}(z) \cos \left( \frac{2k \cdot \alpha_{sw} - \omega_0 t}{2} \right) \right\} ight] \]

(2)

being \( J_k \) the Bessel function of the first kind of the order \( k \),

\[ z = 2 \beta \cdot \sin \left( \frac{\omega_0 \tau}{2} \right) \]

where \( \beta \) is the frequency modulation index and being

\[ \tau = \frac{1}{\text{FSR}} \]

where FSR is the free spectral range of the periodic bandpass filter. In the experiments, the periodic bandpass filter was implemented using a Mach Zehnder Interferometer (MZI), in which \( \tau \) is the differential delay between the arms of the MZI. Therefore, the received harmonics are as follows

\[ X = |E_0|^2 \cdot \cos(\omega_0 \tau) \cdot J_{2k} \left( 2 \beta \sin \left( \frac{\omega_0 \tau}{2} \right) \right) \]

(3)

for the even harmonics and

\[ Y = |E_0|^2 \cdot \sin(\omega_0 \tau) \cdot J_{2k-1} \left( 2 \beta \sin \left( \frac{\omega_0 \tau}{2} \right) \right) \]

(4)

for the odd harmonics

As we can observe in the equations, the strength of the harmonics strongly depends on \( \beta \), on the sweep frequency and on the FSR value of the filter. By optimizing \( \beta \), the intensity of a specific higher harmonics can be maximized. In the experiments, two different values of the FSR could be used to compare the performance for the considered transmission frequencies.

#### III. EXPERIMENTAL SETUP

The proposed setup for our experiment is depicted in Figure 2; a tunable DFB laser source at 1550nm with an intensity modulator was biased with \( V_{bias} \) to maximize the amplitude of the received signals. The modulated optical signal was then amplified by means of an Erbium Doped Fiber Amplifier (EDFA), optically filtered to reduce the ASE noise, and filtered once again by the MZI to perform the FM-IM conversion before its transmission through the standard SMF link. For the experimental demonstration, two different MZIs were used: the first one with a FSR1=20GHz and insertion loss of 14dB, and the second one with a FSR2=40GHz and insertion loss of 12dB.

In both cases, the considered transmission distances ranged from 0km up to 125km. The scheme for distances up to 50km is shown in Figure 2-setup 1, using a second EDFA before the reception block, whereas Figure 2-setup 2 shows the setup for lengths up to 125km, where the second EDFA is placed after a first span of 50km and before a second one with lengths up to 75km. A variable optical attenuator (VOA) was used before the photodetector in order to keep a constant received power of 0dBm. After the 38GHz bandwidth photodetector and an electrical amplification stage, the radio data signal was demodulated and analyzed in the vector signal analyzer (VSA).

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In order to maximize the power of the desired harmonics, the parameters of the system were optimized for a back-to-back configuration for the two available MZIs and afterwards these parameters remained the same for the different transmission distances. For that purpose, and for each \( f_{\text{sw}} \), the value of \( \beta \) was set between 4 and 5 by setting the input power to the PM to values between 23dBm and 28dBm, and the optical carrier frequency was tuned close to the MZI notch. The intensity modulator was biased with a voltage about 1V to increase the received power of the data signals.

Figure 3 shows the spectrum of the received signals in back to back configuration for different FSR and sweep frequencies. As we can observe, when \( f_{\text{sw}1} \) is used, Figure 3-(a), the received power of the 2\(^{nd} \) and 3\(^{rd} \) harmonics is significantly higher than the 4\(^{th} \) and subsequent when the MZI with FSR1 is used. However, when using the MZI with FSR2, the power of the 4\(^{th} \) and 5\(^{th} \) is equalized to the lower ones. In the case of \( f_{\text{sw}2} \), Figure 3-(b), we can observe how the 2\(^{nd} \) and 4\(^{th} \) harmonic increase in power, whereas the 3\(^{rd} \) one presents lower received power when the MZI with FSR2 is used. Finally, for the last case where the sweep frequency is \( f_{\text{sw}3} \), as shown in Figure 3-(c), there are no significant differences between the harmonic strength of the 2\(^{nd} \) and 4\(^{th} \) harmonic, while the 3\(^{rd} \) harmonic power is slightly reduced. The FSR value of the MZI is hence a critical parameter of the system and must be carefully adjusted; in equations (3) and (4), we can observe that by changing the FSR, the argument of the Bessel function can be changed, and thus the strength of the harmonic is affected.

However, the performance of the received signals and the strength of the different harmonics may be strongly affected depending on the link length. This is resumed in Figure 4, where the received EVM of the received 64QAM signal is plotted as a function of the distance. Here also, the three different sweep frequencies in combination with the two possible combination of the MZI are shown. The fiber length was varied from 0km to 125km. In any case, we may observe that for specific combination of the generated frequencies and the MZI used, the EVM response presents fluctuations along the fiber link. These fluctuations are stronger when high frequencies harmonics are generated. This is due to residual effects of the fiber chromatic dispersion, which is more noticeable with SMF, using the OFM technique [2][3][6].

For instance, for the transmission of the data signal at 32.5GHz [Figure 4-(a)], and 36.9GHz [Figure 4-(b)], the system is more affected by dispersion when compared to the others microwave frequencies. In the case of 32.5GHz, the limit of EVM1 and EVM2 could only be met for specific fiber distances. In any case, better performance is observed when using the MZI of FSR1, where distances up to 100km can be achieved regarding the limit of EVM2. However, the performance for 36.9GHz is also better when the MZI with FSR1 is used for the first 75km, but fluctuates for larger distances. Here we can observe that the EVM increases initially due to the fiber attenuation but improves its performance from distances of 50km, even achieving EVM values below EVM1 with FSR2, and meeting the limit of EVM2 when the MZI with FSR1 is used, in both cases reaching distances up to 100km. This is caused by the enhancement of the FM-IM conversion due to the chromatic dispersion, increasing the received power of the harmonic in spite of the fiber losses [3]. For the transmission of the radio data signal at 29GHz [Figure 4-(c)] obtained from \( f_{\text{sw}3} \), low performance values below EVM2 are guaranteed up to 125km when FSR2. Additionally, the limit for EVM1 could be met up to 100km for large distances of fiber, higher than 50km. Here, the performance when using the MZI of FSR1 is significantly reduced. In the case of the lower frequencies, these are 18.7GHz [Figure 4-(b)], 19.5GHz [Figure 4-(c)] and 19.7GHz [Figure 4-(a)], the best performance results were achieved. In all cases, the received signal showed a performance value lower than EVM1, almost independent on the MZI FSR. In this case, transmission distances of 125km were achieved for 18.7GHz, using both MZI, whereas these distances could be reach for 19.5GHz when the MZI with FSR2, and for 19.7GHz when FSR1 was used. In any case, the limit of EVM2 could be met for all distances. It should be stated that

![Figure 3. Harmonics generated in back to back modulated by 64QAM data signal @ 25MS/s allocated at 500MHz in both cases with FSR=20GHz and FSR=40GHz](image-url)
the signal bit rate transmitted in this experiment is larger than
the one recommended by the IEEE standard. Improved
performance results should be expected operating at the
standard bit rates. Moreover, optimizing the received signal
for each distance could further improve the performance
results.

V. CONCLUSIONS

By means of the OFM technique, we have demonstrated
the generation and transmission of different microwave and
millimeter-wave frequencies. Our experimental study
demonstrates the generation and transmission in the third
window of a 64-QAM radio data signal (data rate of
150Mb/s) meeting the limit of EVM=7.943%, through fiber
links up to 125km, at microwave and millimeter-wave
frequencies of 18.7GHz, 19.5GHz, 19.7GHz and 29GHz.
Distances up to 100km have also been reached at 36.9GHz
and 32.5GHz respectively for the same EVM specification.
We have also experimentally proved that the limit of
EVM=5.623% could be met for transmission frequencies of
18.7GHz, 19.5GHz and 19.7GHz for distances up to 125km,
and for distances up to 100km when transmitting with 29GHz
and 36.9GHz. The FSR of the MZI filter is a critical parameter
and must be carefully adjusted for each transmission
frequency and for minimum dependence on fibre link length
to achieve the required performance for the system.

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REFERENCES

[1] Anthony Ng’oma, “Radio-over-Fibre Technology for Broadband
Wireless Communication System,” Eindhoven: PhD thesisTechnische

dispersion tolerance of the Optical Frequency Multiplication technique
for Radio over Fiber over Single mode Fiber”, Proc. BroadBand
Europe Workshop (We2B2), 3-6 December 2007, ISBN

Verdurmen and J.P. Turkiewicz, “Dispersion tolerant radio over fibre
transmission of 16QAM and 64QAM radio signals at 40GHz”,

for in-building Broadband Wireless Services”, Eindhoven: PhD


fibre/wireless LAN access networks,” in Broadband Optical Access
Networks and Fiber-to-the-Home: System Technologies and