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Reconfigurable multi-band radio-frequency transceiver based on photonics technology for future optical wireless communications

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Abstract: This study presents the concept and the implementation of a fully photonics-based and reconfigurable multi-band radio-frequency (RF) transceiver for future optical-wireless communications networks. The proposed device is based on frequency multiplication using optical external modulation technique, which enables to achieve discrete tuning of the wireless frequency by simply manipulating the modulator bias voltage. The physical mechanism behind the frequency multiplication is analytically explained and experimentally demonstrated by generating RF carriers at 5.2 GHz with signal-to-noise ratio of up to 54 dB. High spectral purity, distortion absence and low phase noise of the generated RF signals have been observed. Furthermore, the photonics-based reconfigurable RF transceiver has been implemented and tested in a real optical-wireless network from the telecom operator Telecom Italia Mobile using a femtocell base station. Data transmission and a high-quality voice call have been realised using the proposed approach in order to illustrate its applicability.

1 Introduction

Mobility and capacity have been highly desirable for new telecommunications networks because of the continuous increase in the global data traffic and exponential growth of Internet connections worldwide. Wireless systems and mobile devices available in the market can achieve mobility, whereas capacity solution mainly refers to the optical communications and the use of higher frequencies, such as millimetre-waves, for future wireless networks. Additionally, future telecommunications networks will demand the use of convergent technologies in order to satisfy the requirements of fixed and mobile users that use different protocols and technologies. Microwave photonics (MWP) represents a potential candidate to simultaneously fulfil these demands. This area has brought new functions to microwave systems by taking advantage of the union between optoelectronics and radio-frequency (RF) engineering [1]. Its initial rationale was to use the advantages of photonic technologies to provide functions in microwave systems that are very complex or even impossible to carry out directly in the RF domain. However, MWP is also succeeding in incorporating a variety of techniques used in microwave engineering to improve the performance of photonic communication networks and systems. MWP techniques offer unique features for the processing of microwave, millimetre-wave and RF signals. MWP techniques have been efficiently applied to radar systems [2], wireless communications [3], analogue-to-digital conversion [4], photonics-based microwave filters [5], cognitive and adaptive radio-over-fibre networks [6] and optically controlled reconfigurable antenna arrays [7].

Photonics has been insistently proposed as a potential solution to fill the gap between the urgent need for digital solutions and the limitations of electronics at higher frequencies: the flexibility, wide bandwidth, and technological maturity of photonics in fact have led to numerous proposed architectures for the generation, manipulation, detection and distribution of RF signals [8]. As the carrier frequency increases, these tasks become more and more challenging, because of electronic limitations, distortion, complexity and higher costs. Complementarily, the generation of carriers up to few GHz on optical domain enables advantages as weight, size and consumption reduction, electromagnetic interference immunity, high purity sources and increase cost effectiveness by simplifying the devices involved and flexibility achieved. Finally, the generation of multiple signals is sought for frequency agility and for multi-band wireless communications.

This work presents our concept and implementation of an entire photonics-based and reconfigurable multi-band RF transceiver for future optical-wireless communications networks. The proposed device is based on frequency multiplication using optical external modulation technique, which enables to efficiently reconfigure the wireless frequency by manipulating the modulator bias voltage. The manuscript is structured in six sections. Section 2 presents an analytical explanation on the physical mechanism behind the frequency multiplication and a brief comparison among the optical external modulation technique and other methods reported in literature. Section 3 is concerning a detailed experimental investigation of the photonic-assisted frequency doubling up to 10 GHz as a function of diverse electrical and optical parameters. Sections 4 and 5 report two different experiments that were carried out in order to illustrate the applicability of the proposed device to future convergent telecommunications networks: a convergent and reconfigurable optical-wireless network for long-term evolution (LTE) and wireless fidelity (Wi-Fi) offloading applications; the photonic-assisted multi-band transceiver implementation in a real optical-wireless network from Telecom Italia Mobile (TIM) operator. Finally, Section 6 presents the relevant conclusions and future work.

2 Photonics-assisted generation of tunable microwave signals

Tunable microwave and millimetre-wave signals can be easily generated by using the optical beating method [9]. The optical signals from two lasers tuned at different wavelengths beat at a photodetector (PD) and the electrical signal resulting is described by

$$\mathrm{RF}_{\mathrm{out}} = M\cos[(\omega_1 - \omega_2)t + (\varphi_1 - \varphi_2)] \quad (1)$$

where M is a constant given by amplitude terms and photodetector responsivity, ω_1 and ω_2 are the angular frequencies of optical waves and φ_1 and φ_2 are their correspondent phases. As can been seen from (1), the resulted field is a microwave signal whose frequency corresponds to the wavelength spacing, which is only limited by the photodetector bandwidth [9]. However, the correlation lack between the lasers makes it desirable phase controlled to obtain low phase noise signals, and this procedure usually is laborious. Few years ago several techniques have been proposed to achieve phase stability and increasing efficiency in photonic processing, as dual-wavelength laser, optical injection locking and optical phase-lock loop [10].

High-quality microwave and millimetre-wave signals can also be generated by frequency up conversion principle, in which a low-frequency signal is taken as reference. Diverse optical approaches have demonstrated the photonic up conversion, using the following components: an intensity single-drive modulator [11]; a phase modulator [12]; a dual-electrode modulator [13]; and integrated modulators [14]. Additionally, Vidal [15] has proposed to use cascaded four-wave mixing and polarisation pulling for realising photonic up conversion. Nevertheless, it is a very complex procedure because of the desirable non-linear effects control.

The microwave and millimetre-waves generation based on external modulation has been showing potentially interesting for communication systems because of its low cost and simplicity. It works as an optical up-converter to increase the drive signal frequency in accordance with a multiplication factor (k) established. The last one can be configured to 1, 2, 4, 6, 8 and 12, depending on the scheme applied [16–18]. Photonic frequency doubling was first proposed in 1992 as a way to provide very narrow line width signals, when a 36 GHz carrier was generated [19] and distributed for remote delivery of video services [20]. The main advantages of this method, in addition to simplicity, are high spectral purity, low phase noise, high frequencies supported and tunability. It is based on only one distributed feedback laser, a single drive Mach-Zehnder modulator (MZM) and a PIN (p-intrinsic-n diode) photodetector, as presented in Fig. 1.

An optical carrier locked at λ_0 and a RF signal centred at f, are injected to the optical external modulator via its optical and RF ports, respectively. The electrical wave composed by the sinusoidal modulating voltage is given by [20]

$$V(t) = V_\pi(1+\varepsilon) + \alpha V_\pi \cos(\omega t) \tag{2}$$

where ω and α are the frequency and normalised amplitude of the input RF signal, respectively, and ε is the normalised bias point of the modulator. The MZM output optical field is usually described by [20]

$$E_{\text{out}}(t) = E_{\text{in}}(t)\cos\left(\frac{\pi}{2}\cdot\frac{V(t)}{V_\pi}\right) \tag{3}$$

where $E_{\text{in}}(t)$ is the optical laser signal, thus MZM output optical field can be expressed by [20]

$$E_{\text{out}}(t) = \cos\left\{\frac{\pi}{2}[(1+\varepsilon)+\alpha\cos(\omega t)]\right\}\cos(2\pi L t) \tag{4}$$

in which L is the optical carrier frequency. This field can also be written by Bessel function in order to make its interpretation easier [20]

$$\begin{aligned} E_{\text{out}}(t) = {} & \frac{1}{2}J_0\left(\frac{\alpha\pi}{2}\right)\cos\left[\frac{\pi}{2}(1+\varepsilon)\right]\cos(2\pi L t) \\ & - J_1\left(\frac{\alpha\pi}{2}\right)\sin\left[\frac{\pi}{2}(1+\varepsilon)\right]\cos(2\pi L t \pm \omega t) \\ & - J_2\left(\frac{\alpha\pi}{2}\right)\cos\left[\frac{\pi}{2}(1+\varepsilon)\right]\cos(2\pi L t \pm 2\omega t) + \cdots \end{aligned} \tag{5}$$

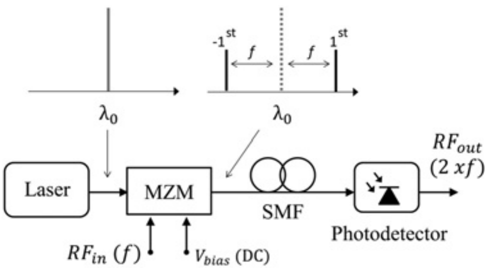

Fig. 1 *Optical external modulation technique for frequency multiplication*

where $J_n(x)$ is the nth-order Bessel function. This expression refers to an optical spectrum composed by the optical carrier and some sidebands, separated by the RF input signal. It works in this manner for conventional applications, in which the photodetected signal does not vary in frequency. However, according to (5), if the MZM is biased at the minimum transmission point (MITP), V_{bias} set to V_π ($\varepsilon = 0$ condition), the optical carrier is suppressed and its output spectrum is composed only by the first-order sidebands spacing of $2f$. The beat of these components at PD results in an output RF signal whose frequency is twice higher than that of the RF input signal. It means that a k factor equal to two is achieved and, consequently, the RF frequency carrier is doubled. One penalty for this condition is a significant electrical power reduction because of the modulator operation at MITP, but its several attractive features can overcome it. Moreover, using RF amplifiers can easily compensate this drawback.

If the MZM is biased at the maximum transmission point, at the output of the MZM, an optical signal with an optical carrier and two second-order sidebands are generated. By using a notch filter to remove the optical carrier, and then beat the two sidebands at the PD, a frequency quadrupled microwave signal is generated. Two cascaded MZMs can be employed to generate a microwave signal with a higher multiplication factor. The multiplication factor can be as high as 12, which enables the generation of a high-frequency microwave or terahertz signal using a low-frequency microwave source.

3 Experimental validation of frequency doubling using optical modulators

This section presents a detailed experimental investigation of the photonic-assisted frequency doubling using the optical external modulation technique as function of some electrical and optical parameters. The experimental setup is based on the following pieces: a 4 dBm continuous laser at 1551 nm; a single drive MZM; a PIN photodetector; a power supply; a RF signal generator; and electrical signal analyser.

Initially, the MZM optical and electrical powers have been evaluated as a function of the modulator bias voltage, as reported in Fig. 2. The RF input signal power and frequency were 12 dBm and 2.6 GHz, respectively. The modulator bias voltage from a DC source has been properly managed in order to ascertain the multiplication factor and demonstrate the possibility to reconfigure the RF frequency. A cyclic behaviour is observed in the optical power, as well as the generation of a RF carrier 5.2 GHz because of the photonic-assisted multiplication of the driven signal at 2.6 GHz. Biasing the modulator at 3.1 V (V_π) implies in carrier suppression, $k = 2$, and a power increase in the duplicated signal by means of photonic-assisted multiplication of the input RF signal. At the points where the 5.2 GHz carrier is maximum, the 2.6 GHz signal is minimum. Similarly, at those points where $k = 1$, the duplicate signal power is reduced to the minimum value. The two insets of Fig. 2 report optical spectrum measurements for 3.1 and 4.5 V obtained using an optical spectrum analyser with 0.1 nm resolution before the photodetection process. These insets illustrate the carrier suppression and high modulation index states.

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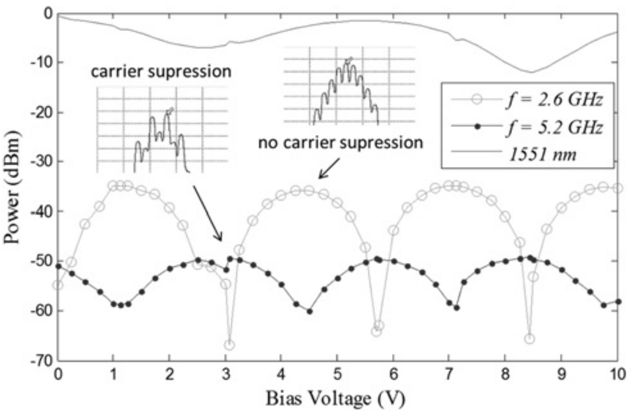

Fig. 2 *Experimental analysis of the optical and electrical powers as a function of the bias voltage*

Two insets present the measured optical spectra for 3.1 and 4.5 V

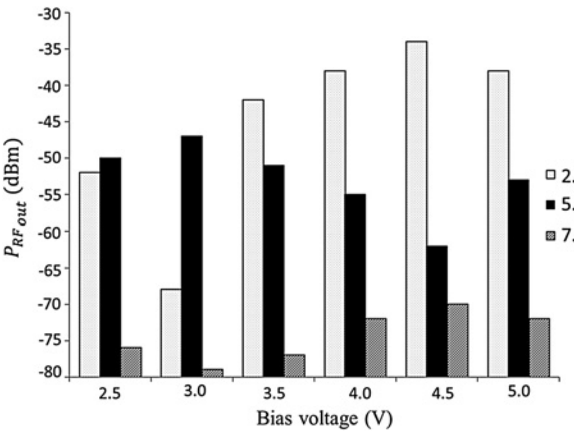

Fig. 3 *Frequency reconfigurability as a function of the MZM bias voltage*

It is clear that the generated frequency depends exclusively on the modulator bias voltage. The bias voltage equal to 3.1 and 4.5 V stand out as potential values for making the optical-wireless network reconfigurable, since they provide the highest level and best signal-to-noise ratio (SNR) for 2.6 and 5.2 GHz signals, respectively. Therefore the network can operate at 2.6 and 5.2 GHz or at both bands simultaneously. This reconfigurable functionality is efficiently illustrated in Fig. 3, which presents the RF output power ($P_{\mathrm{RF_{out}}}$) for different frequencies as a function of the bias voltage. Biasing at 2.5 V enables to operate with the 2.6 and 5.2 GHz carriers simultaneously, since their power are very similar. The presence of a spectral component at 7.8 GHz, which comes from the photodetection process, is also observed. However, its power level is very low and the RF spurious suppression ratio (RFSSR) is typically higher than 30 dB.

Fig. 4 shows the measured electrical spectra of the generated microwave signal for $V_{\mathrm{bias}} = 4.5$ V ($k = 1$) and $V_{\mathrm{bias}} = 3.1$ V ($k = 2$), in which very high spectral purity and distortion absence can be noted in both the cases. As expected, the electrical power of the 5.2 GHz signal is reduced because of the optical carrier suppression on the photonic processing. An increase in the laser power or the use of an optical amplifier can equalise it.

The power at the optical modulator RF port is another degree of freedom of the proposed photonic-assisted multi-band transceiver. Two cascaded RF amplifiers have been used at RF signal generator output in order to illustrate the possibility of further reconfigure the transceiver operation. The first one is amplifier with a noise figure NF = 4.5 and a gain $G = 17$ dB, whereas the second one is a low noise amplifier that provides NF = 0.7 and $G = 7$ dB. Their use enables to increase the RF power up to 20 dBm, which is the maximum level tolerated by our MZM. Fig. 5 presents an experimental investigation of the photodetector RF output power ($P_{\mathrm{RF_{out}}}$) as a function of the MZM RF input power ($P_{\mathrm{RF_{in}}}$) for $V_{\mathrm{bias}} = 3.1$ V ($k = 2$). Note that the level of 5.2 GHz carrier significantly increases as the driven signal power is increased. However, the power level at 7.8 and 10.4 GHz also increases, implying in a reduction of the RFSSR parameter. Therefore for working at high power levels at the MZM RF port, it becomes necessary to evaluate not only SNR, but also RFSSR. For instance, SNR = 54 dB is obtained by driving at 20 dBm, but RFSSR is only 19 dB. The proposed transceiver provides a good compromise for $P_{\mathrm{RF_{in}}}$ between 12 and 16 dBm, which provides SNR from 42 and 49 dB and RFSSR between 30 and 27 dB, respectively.

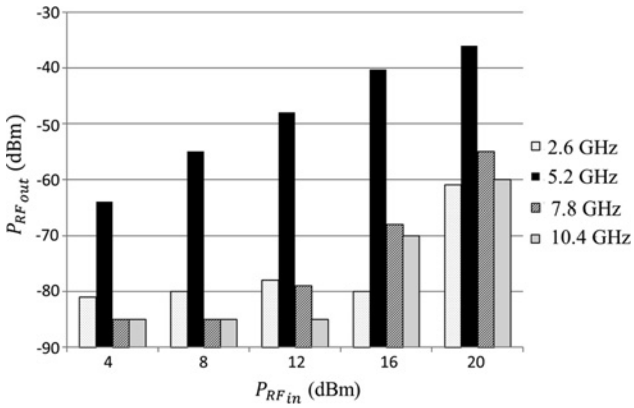

Fig. 5 *Photodetector RF output power as a function of the MZM RF input power for $V_{bias} = 3.1$ V ($k = 2$)*

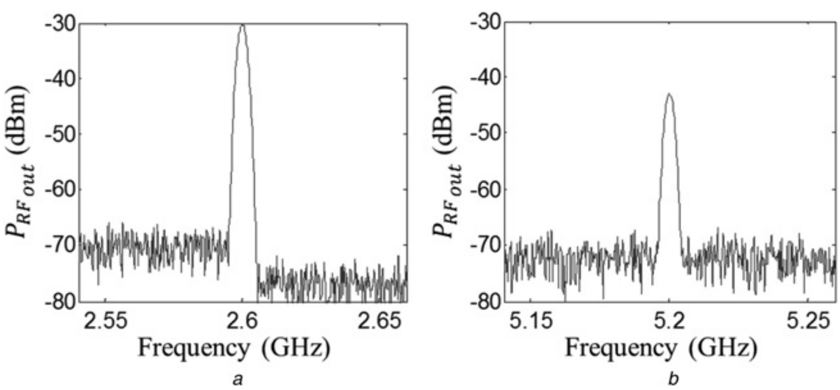

Fig. 4 *Measured electrical spectra for different multiplication factors*

Finally, we have experimentally evaluated the stability of the proposed transceiver, over 1 h, under a condition in which the input source parameters may not be perfectly controlled and those sources and the photodetector have corrupting noise. First, we replaced the commercial power supply, previously used to bias the MZM, by a basic homemade voltage source, instability of ±77.5 mV and ripple of 300 mV, in order to investigate the sensitivity of the frequency and amplitude drifts. As a result, an amplitude oscillation of ±0.25 dB in the generated RF carrier and a maximum reduction of 6.0 dB in the RFSSR parameter were observed. Furthermore, we have obtained a maximum RF power variation of ±2.0 dB and frequency oscillation of ±26 kHz in the worst case using the following components: a highly noise photodetector; a RF signal generator with amplitude variation of ±0.5 dB and frequency instability of ±5 ppm around 2.6 GHz; RF amplifiers with noise figure NF = 5 dB at the modulator RF.

4 Convergent and reconfigurable optical-wireless network

We propose to apply the reconfigurable multi-band RF transceiver based on photonics technology to create a convergent and reconfigurable optical-wireless network, as described in Fig. 6. It takes advantage of optical and wireless technologies in a unique network. The main advantages from the optical side are extremely low attenuation, reduced size and power consumption and weight, as well as electromagnetic immunity. On the other hand, wireless technologies provide mobility and flexibility. Furthermore, the proposed network provides the functionality of the frequency reconfiguration by taking advantage of the optical external modulation technique. In this way, it is possible to reconfigure the electrical carrier as a function of traffic demand and radio mobile propagation aspects. The optical backhaul interconnect many remote units. The proof of concept was aimed for LTE at 2.6 GHz and Wi-Fi at 5.2 GHz standards, which operate in two different frequency bands, thus requires the use of a reconfigurable technology.

As demonstrated in the previous section, manipulating the MZM bias voltage can efficiently reconfigure the transceiver frequency operational band. Therefore by applying a drive signal of 2.6 GHz at MZM RF input and tuning its bias voltage, one can obtain a k factor equal to one or two. These values correspond to the generation of signals at 2.6 and 5.2 GHz, respectively, and the frequency selection is simply determined by the modulator bias voltage V_{bias} adjustment. As a result, the convergent and reconfigurable optical-wireless network is able to provide two different electrical carriers for wireless environment and, consequently, enable their use independently or simultaneously in accordance to traffic demand and radio mobile propagation aspects. A telecom operator can use the proposed photonic-assisted transceiver to perform mobile data offloading using Wi-Fi standard in the 5.2 GHz industrial, scientific and medical (ISM) band as a complementary network technology, with the purpose of delivering data originally targeted for cellular networks. This technical solution can be applied to reduce the congestion of cellular networks. It is expected that mobile data offloading will become a new industry segment because of the surge of mobile data traffic. The proposed network can be used for any wireless system, including millimetre-waves for picocell and femtocell applications.

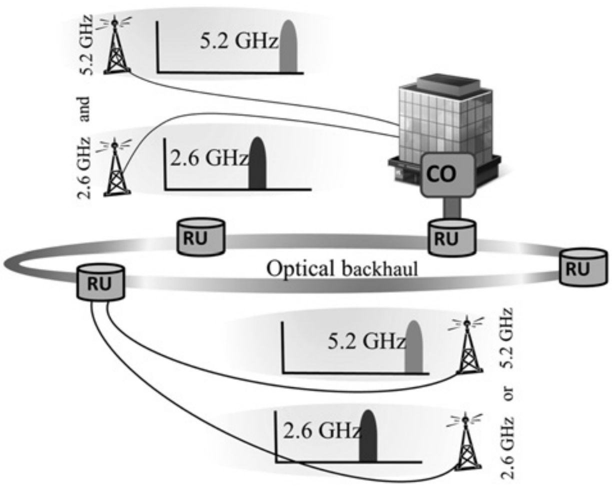

Fig. 6 *Convergent and reconfigurable optical-wireless network for LTE and Wi-Fi offloading applications*

5 Implementation of the photonics-based and reconfigurable multi-band RF transceiver in a real network

The second application is regarding the implementation of the photonics-based and reconfigurable multi-band transceiver in a real cellular network from the telecom operator TIM using a universal mobile telecommunications system (UMTS) femtocell base station (BTS), as proposed in Fig. 7. Our main goal is to demonstrate the applicability of our reconfigurable transceiver for UMTS at 2.1 GHz (3G), LTE at 2.6 GHz (4G) and Wi-Fi at 5.2 GHz (mobile offloading) applications. Its use enables to provide any combination of these three wireless standards using a reconfigurable optical-wireless network.

Similarly to the network presented in Section 4, the current proposed scheme uses frequency multiplication based on the optical external modulation technique by tuning the modulator bias voltage. The main difference is the use of two RF signals at different frequencies for driving the optical modulator. We have used a 2.6 GHz signal from the RF signal generator vector signal generator (VSG) and a 2.1 GHz signal from a UMTS femtocell, called 'Blue Zone TIM', which was connected to the real network from the telecom operator TIM. Both signals have been set to 14 dBm. The optical-wireless network will operate with 3G and 4G standards for the multiplication factor $k = 1$, since the 2.1 and 2.6 GHz carriers were present at the photodetector output. On the other hand, if $k = 2$, three carriers are generated at 4.2, 4.7 and 5.2 GHz, of which the last one refers to the Wi-Fi band.

Fig. 8*b* displays a photograph of the implemented optical-wireless network based on the following pieces: a femtocell BTS, a RF combiner, a RF signal generator, one kilometre of single-mode fibre, a broadband antenna, two mobile phones, a 4 dBm continuous laser at 1551 nm, a single drive MZM, a PIN photodetector, a power supply and an electrical signal analyser. First, two mobile phones are used to make calls and surf on Internet using the conventional UMTS network form, called TIM. Fig. 8*a* demonstrates that the TIM mobile network is working properly. The next step was applying the proposed optical-wireless architecture and increases the power level, in such way that it becomes higher than the convention TIM network in order to enable the voice

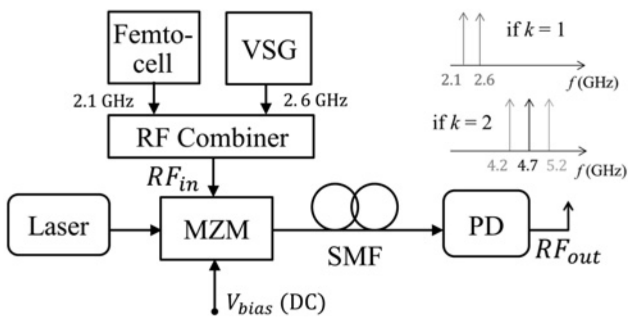

Fig. 7 *Implementation of the photonics-based and reconfigurable multi-band RF transceiver in a real network from the telecom operator TIM*

Fig. 8 *Implementation of proposed optical-wireless network*

a Mobile phone screen illustrating communication using the conventional network
b Photograph of the entire experimental setup
c Femtocell and mobile phones
d Mobile phone screen illustrating communication using the 'Blue Zone Tim' (femtocell)

and data communication using our photonic-assisted multi-band transceiver based on the UMTS femtocell. Fig. 8*c* demonstrates the femtocell BTS LED is on, which indicates it is in operation, whereas Fig. 8*d* reports the network used by the mobile phone changed to 'Blue Zone TIM', proving the proposed transceiver worked properly. Furthermore, a high-quality call was done through the proposed network, as well as data transmission through Internet.

6 Conclusions

This work presented our concept and practical implementations of a fully photonics-based and reconfigurable multi-band RF transceiver for future optical-wireless communications networks. The proposed device is based on frequency multiplication using optical external modulation technique, which enables to reconfigure the wireless frequency by simply manipulating the modulator bias voltage. The physical mechanism behind the frequency multiplication was analytically explained and experimentally demonstrated by generating RF carriers at 5.2 GHz with SNR of up to 54 dB. High spectral purity, distortion absence and low phase noise of the generated RF signals have been observed. Two different scenarios were carried out in order to illustrate the applicability of the proposed device to future convergent telecommunications networks: a convergent and reconfigurable optical-wireless network for LTE and Wi-Fi offloading applications; the photonic-assisted multi-band transceiver implementation in a real optical-wireless network from TIM operator. Data transmission and a high-quality voice call have been realised using the proposed transceiver. Future works regards the application of the proposed photonic-assisted multi-band transceiver for software-defined radar applications.

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