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# Microwave Photonics Mixing

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**Abstract.** *The multidisciplinary field of Microwave-Photonics is at the convergence of photonic and microwave or even wireless technologies. In this context, the processing, conversion and transmission of microwaves, as well as high data rate digital and wireless signals, today use broadband optical techniques with many applications. However, the frequency band available is frequently changing with up-to-date commercial standards, and it is necessary to up- or down- convert the frequency of the electrical signals using a suitable optical approach for mixing. This paper intends to give an overview on the optical techniques used for frequency conversion, i.e. mixing, and gives the advantages and drawbacks of all techniques presented.*

**Keywords:** *Microwave-photonics; Mixing; Wireless systems; Millimeter-wave; Ultra wide-band.*

## INTRODUCTION

Nowadays, there is great interest in commercial exploitation of the millimeter-wave (MMW) spectrum around 60 GHz, because the fractional available bandwidth is wider, the antennas are smaller and attenuation of the atmosphere allows a reduction in interference from adjacent cellular systems. Since the classical direct generation of millimeter wave signals is expensive using conventional electronic techniques, up-conversion to 60 GHz is an attractive solution that can be done optically to profit from the huge bandwidth of the fiber.

Much progress in microwave-photonics techniques has been made since the 1996 first International Topical Meeting on Microwave Photonics (MWP) [1-3]. Efficient solutions are given, not only for transport, but also for processing signals like microwave, millimeter wave, wireless and digital. Transport is done via optical fiber networks with attractive results, since fiber has a low loss of 0.2 dB/km, is immune to interference, and is capable of transmitting very large bandwidth signals. Efficient processing like all-optical filtering and mixing is achieved using performing components and innovative systems. The European Commission has funded a number of projects in microwave photonics, among which are ISIS, IPHOBAC and UROOF [4] in which photonics are used for MMW signal processing and where huge progress has been shown both at component and system levels in terms of performance and flexibility, respectively.

This paper gives an overview of the field of optical processing and, in particular, mixing for up-and down-frequency conversion. Since optical components can be modulated by MMW signals at rather low cost with broadband efficiency, results using specific optical components and systems have been reported recently, and are summarized here. The following topics covering various frequency ranges will be addressed:

(i) Wide band photonic techniques for microwave mixing.

(ii) Results with microwave-photonic systems based upon the merging of microwave and photonic technologies.

Comparisons will finally summarize the advantages and drawbacks of all methods.

## MICROWAVE-PHOTONICS TECHNIQUES FOR MIXING

Although optical generation of MMW signals is possible by optical heterodyning or frequency multiplication using non linear fibers, this paper is limited

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to giving methods for optical frequency conversion; so called microwave-photonics mixing where a remote Local Oscillator (LO) signal is used with a non-linear device to up- or down- convert an Intermediate Frequency (IF) signal to a Radio Frequency (RF) band. Applications are in sensors, radar systems and telecommunication cellular systems as well, all requiring wide band processing and remote antenna [5]. In some cases, many microwave sub-carriers have to be converted optically [6]. The huge bandwidth of the fiber and low weight are here precious advantages, well adapted to the remote transmission of broadband signals. Important progress in photonic components like distributed feedback laser sources (DFB), vertical surface emitting lasers (VCSELs) and External Optical Modulators (EOMs) allows the efficient processing of microwave signals. Their system implementation requires accurate modeling [7-15].

In a conventional scheme without frequency conversion, the RF signal to be radiated to the antenna is either externally modulated onto the optical carrier by an EOM, or directly modulated by the Laser Diode (LD). The transmission suffers from the dispersion effect of the fiber when the RF frequency is high or when it is transmitted over long distances [16-19]. In that case, the chromatic dispersion of the fiber limits the maximum MMW signal frequency, and there is a need for processing at the remote end of the optical link. Then, at lower IF, the signals can be transmitted over longer distances. The other scheme, addressed in this paper, uses frequency conversion or mixing on the optical link of an IF signal. In both schemes, the RF signal is carried by the optical field of the fiber and may be optically amplified if necessary. The photo-detected RF signal is then amplified electrically and radiated to the antenna. Architectures using remote antenna and frequency conversion up to the 7th harmonic of the LO have been demonstrated to minimize the effect of dispersion with external modulation and digital modulation formats like QAM, PSK and ASK [20].

For example, in radio over fiber systems supporting wireless networks like Personal Area Networks (WPANs), Wireless Local Area Networks (WLANs) and 3rd generation mobile communication systems, low cost Base Stations (BS) are connected via fibers to a Central Office (CO). Signal routing and processing is done at the CO rather than at the numerous BS. To avoid the effect of chromatic dispersion, lower frequency LO signals are distributed from the CO, and frequency remote up-conversion is done at the BS [21]. Low cost commercial components can then be used at the BS when the up-conversion is done there. Moreover, the generation of high frequency by optical up conversion imposes less stringent requirements on the modulation bandwidth of optical modulators, thus decreasing their cost.

From the above examples, it appears that different methods for mixing must be considered, which differ by:

(i) The location of the up-conversion process, either at one or the other end of the optical link.

(ii) The LO frequency range, since the chromatic dispersion effects of the fiber impose length limitation, depending on RF frequency transmitted on the optical link and, therefore, the up-conversion process must be closer to the photo-receiver end.

Two configurations can be employed for microwave-photonics mixing, and are examined below.

In the first, “mixing at modulation side”, modulation of the optical carrier and IF to RF up- or down-conversion are realized together before transmission on the fiber. This includes mixing using fundamental optical non linearity like four-wave mixing.

In the second, “mixing at the detection side”, photo-detection after optical transmission of the IF signal and up-conversion to RF frequency are done simultaneously.

### Mixing at Modulation Side

A non-linear element has to be inserted in the optical transmission link to generate a mixing signal at frequency $f_{\mathrm{RF}} = f_{\mathrm{IF}} \pm f_{\mathrm{LO}}$ detected at the output of the optical link. Modulation of the light is done either by direct or external modulation of a laser diode, and can profit by Wavelength Division Multiplexing (WDM), a unique possibility of optics [14]. Two different configurations for mixing are applied: two cascaded linear modulations [22-25] or two modulations of a single device working in a nonlinear regime [26,27].

The first configuration uses two cascaded devices, each of them under linear modulation with either LO or IF signals, since cascading linear transfer functions result in the product of each of them; a non-linear operation.

A first example of the application of the first configuration with two cascaded modulations is shown in Figure 1, and has been developed in a collaborative work within a European network of excellence ISIS [4] between the University of Ottawa (Canada) and CNRS-IMEP (France). It uses a Phase Modulator

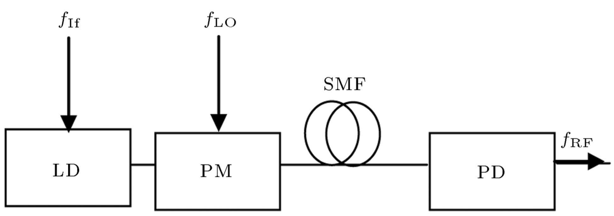


**Figure 1.** Microwave-photonics mixing system with cascaded elements.

(PM) and a dispersive fiber (SMF). This is a very low cost system, since the fiber is the main element for frequency conversion [23,24]. The LD is directly modulated by the IF signal, while phase modulation is realized with a LO signal at a remote port. This technique takes advantage of the chromatic dispersion properties of the fiber inserted between the phase modulator and the Photo-Detector (PD) to convert the Frequency Modulation (FM) of the laser diode and phase modulation into Intensity Modulation (IM). Results are presented in the next section.

A second example of cascaded modulations is based on two external EOM's supporting the IF or LO signals, respectively [25]. The configuration of Figure 1 still applies, but LD and PM are replaced by two EOM's; the optical source not being modulated (CW). Results will be presented in the next section.

The second configuration uses only one opto-electronic device modulated by both LO and IF signals, for example a LD or EOM directly or externally modulated by both LO and IF signals.

One first example of the second configuration takes advantage of laser chirp and non linear FM to IM conversion including phased induced intensity noise conversion [26-29] by using a passive optical unbalanced interferometer integrated on glass substrate, which is a very low cost solution. In this method, a LD of high chirp is directly modulated by LO and IF signals. Nevertheless, temperature stability is necessary to control the coherent interference regime and the frequency bandwidth of this method is limited by the Free Spectral Range (FSR) of the interferometer and the LD bandwidth.

A second example of the second configuration with a direct modulation of a LD uses VCSEL's, which are low-cost components well-suited for wireless access applications [30-34].

The non-linear curve, optical output power as a function of DC bias, is shown in Figure 2 for a typical VCSEL.

When the VCSEL is directly modulated by both LO and RF signals and operated in a non-linear regime, mixing is generated.

While VCSEL's modulation bandwidths are limited to 10 GHz, they are suitable for wireless applications like Wireless Local Area Networks (WLAN's) or Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) Ultra Wide Band (UWB) signals. In MB-OFDM, the up-converted process could therefore allow the covering of one or another band in the 3.1-10.6 GHz UWB range [32,33] for example by frequency hopping. That type of work was extensively developed in the European project UROOF [4]. It has been demonstrated that it is possible to up-convert a UWB monocycle (800 MHz-2.5 GHz) or WLAN signal, beyond the relaxation frequency of the laser diode up

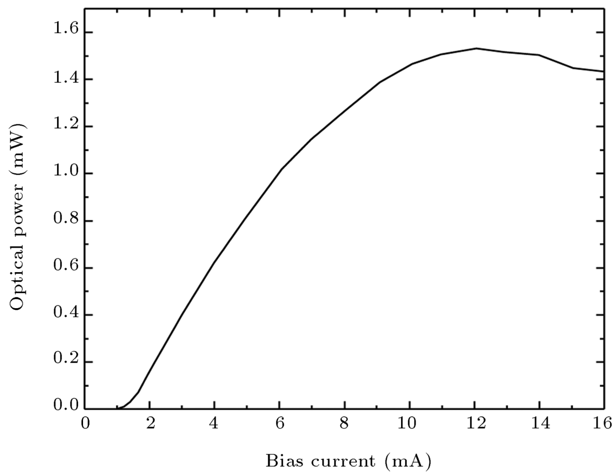


**Figure 2.** VCSEL power-current characteristics.

to frequencies as high as 16 GHz [32,33]. Moreover, it has been found that the best condition for mixing using directly modulated laser diodes is $f_{\mathrm{RF}} = kf_r = mf_{L0} + nf_{\mathrm{IF}}$, where $f_r$ is the resonant frequency of the laser diode [35].

Other optical techniques based on Semiconductor Optical Amplifiers (SOA's) for frequency up-conversion have been reported in the literature [36-41]. The main techniques used are derived from non-linear effects, namely, the four-wave mixing (FWM) [39,40], cross phase modulation (XPM) [36], and cross gain modulation (XGM) [37,38,41]. The simplest technique for all optical wavelength conversion involves XGM. This can be performed by using the pump wavelength to saturate an SOA along with a counter or co-propagating probe wavelength. The pump signals experience the cross-gain modulation induced by the probe [37,41]. The simplicity of the XGM conversion is countered by a limited wavelength conversion range where the extinction ratio of the pump is maintained. The next section reports some results of up-conversion with SOA's achieved within the ISIS European project [4] with comparisons of up-conversion with VCSEL's.

## Mixing at Detection Side

Several authors have investigated the performance of GaAs MESFET's [42] and, more recently, Heterojunction Bipolar Transistors (HBT) [3] under illumination. Optical processing is explored with those devices [3] and with photodiodes also [26,43] for both CW and UWB signals.

When injecting a LO signal at the electrical port of the photodiode and simultaneously illuminating the device by an IF modulated optical signal, mixing of the two signals occurs. The mixing process is explained as a result of the nonlinearity of the PD current-voltage relationship.

The characteristics exhibit the maximum nonlin-

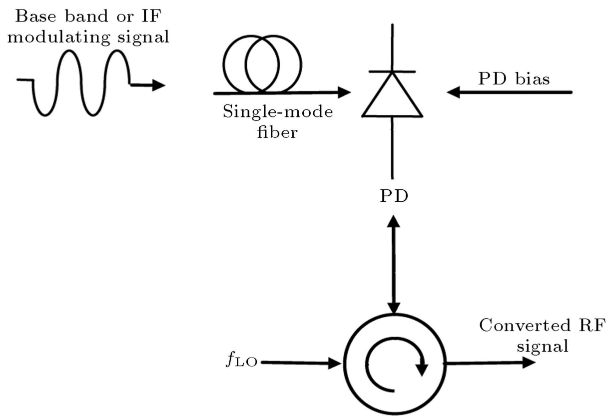


**Figure 3.** Frequency conversion of IF signal by photodiode (PD).

earity in the vicinity of 0 V, which is the optimal operation point for efficient mixing [43].

In the photodiode mixing configuration shown in Figure 3, a baseband data or IF signal is transmitted by the optical fiber. The converted signal is then separated from the LO signal by a circulator before transmission to the RF port [43].

However, for efficient microwave-photonics mixing, some considerations applicable to the above two methods are important to observe. In an optical link made of laser, external modulators, fibers and photo-detectors for up-conversion, the combined effects of laser chirp, electro-optical mixing, dispersive fiber transmission, and photo-detection on the nonlinear signal properties of the electro-optically generated millimeter-wave signal resulting from up-conversion must be considered. They all have been modeled, and their analysis compared to experimental results achieved good agreement [44]. A limited number of model parameters describing the behavior of the above components are essential to predict the mixing signal correctly [44]. They include laser chirp, fiber length and its dispersion coefficient, intensity and phase modulation index.

All methods presented above require filtering to suppress the undesired mixing products. This can be achieved optically with a very good $Q$ factor [45] profiting from the optical link for both transmission and signal processing purposes, which avoids optical to electrical conversion if filtering is made electrically.

Results and applications of the above two methods are given in the next section. The properties of the microwave-photonic mixer, conversion gain, isolation between input ports, and input bandwidth are important figures in comparing all techniques.

## RESULTS

In the transmission systems dedicated to all-optical up-conversion, as described hereafter, the conversion gain of the mixing process is a very important figure of merit and is defined as:

$$\mathrm{CG\ (dB)} = P_{\mathrm{RF}}\ (\mathrm{dBm}) - P_{\mathrm{IF}}(\mathrm{dBm}),$$

where $P_{\mathrm{RF}}$ denotes the power of the converted signal at RF frequency and $P_{\mathrm{IF}}$ is the applied available input power before conversion at IF frequency. This figure will be used to compare all solutions for microwave-photonics mixing.

### Cascaded Modulation

One solution exploring mixing with cascaded modulations is to use an electro-optic Phase Modulator (PM) and a Laser Diode (LD), where the LO and IF signals are applied to a LD and PM, respectively [23,24].

With the natural dispersion of a classical Single Mode Fiber (SMF), simultaneous all-optical microwave mixing and bandpass filtering can be achieved. In works reported in ISIS [4], a subcarrier IF frequency up-conversion from 3.5 GHz to 11.7 GHz over a 25 km dispersive fiber link has been experimentally investigated, with a BPSK modulated signal and a data rate of 172 Mb/s applied to the PM. The mixed optical LO and IF signals after the PM were then applied to the SMF link, serving as a dispersive device, as well as a transmission medium, and other intermodulation products, other than the one desired, were rejected.

A first step is all-optical microwave bandpass filtering. To achieve microwave filtering with very narrow bandwidths, a multi-wavelength fiber ring laser must be used with about 30 wavelengths and a wavelength spacing of 0.2 nm. With this configuration, the RF frequency at the peak of the band-pass filter of 11.8 GHz was determined by the wavelength spacing of the multi-wavelength light source and the accumulated dispersion of the 25-km SMF link [23,24].

A second step is all-optical microwave mixing and bandpass filtering. By applying IF and LO signals to the phase modulator, the up-converted microwave signal at the output of the photo-detector was obtained. The converted signal can be naturally distributed to a remote station over a 25 km span, which provides an added advantage to the proposed system.

For system applications, the performance of the mixer has been evaluated in Figure 4, with a Pseudo Random Bit Sequence (PRBS) $2^7 - 1$ BPSK signal and data rate of 172 Mb/s modulating the IF subcarrier at frequency $f_{\mathrm{SC}}$. A light source composed of two wavelengths generated from two LDs with a wavelength spacing of 0.75 nm was used for experiments. A two-tap notch filter has been, thus, implemented.

In the experiment, the results of which are given in Figure 4, the IF and LO frequencies are 3.5 GHz and 8.25 GHz, respectively, while the LO signal has an output power of 18 dBm. The electrical spectrum at

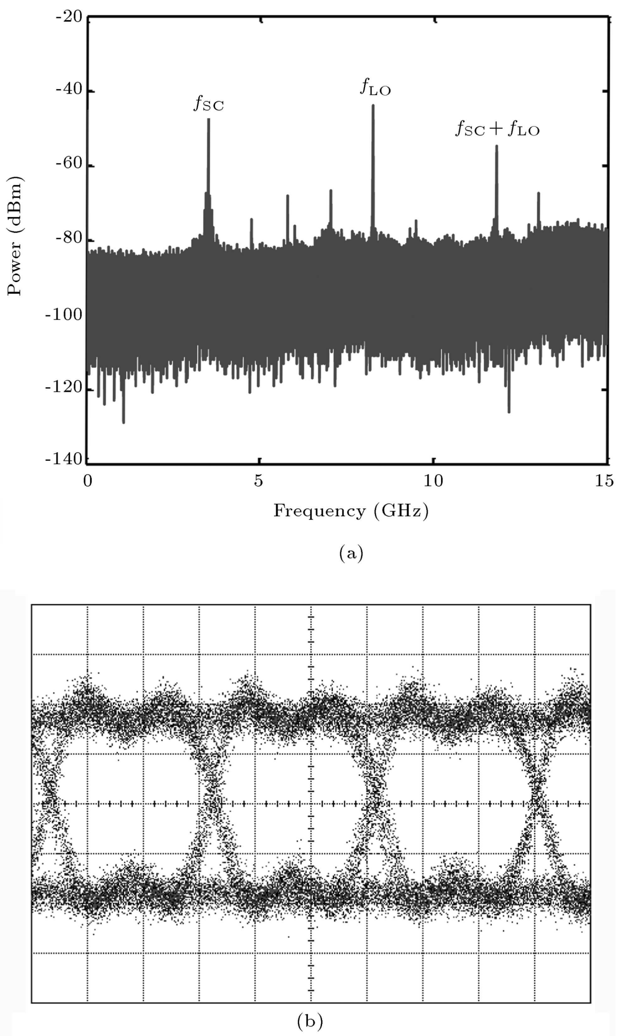


**Figure 4.** (a) Measured electrical spectrum at the output of the photodetector, and (b) measured eye diagram at the receiver when 172 Mb/s PRBS $2^7 - 1$ signal is applied ($X$ axis: 2ns/div).

the output of the photo-detector is shown in Figure 4a. We can see that the power levels of other unwanted inter-modulation products are significantly suppressed. Figure 4b shows the eye diagram of the demodulated PRBS signal, which is clear and wide open, demonstrating that an excellent up-conversion is achieved.

Another solution for exploring mixing with cascaded modulations uses cascaded EOMs. Many RF systems incorporating up and down processing signals and multiple EOMs for up and down conversion have already been used to implement the required frequency conversion in Radio over Fiber (RoF) systems, where one modulator impresses the LO, and the other the IF signal [46]. Some efforts to implement image reject down-conversion [47] or multiple simultaneous down conversions on many RF channels have been made [48] by profiting from one precious advantage of optics in offering Wavelength Division Multiplexing (WDM).

We can now consider applications of microwave photonics mixing to RoF for mobile communications and WLANs [49-52], where the desired mixing frequency at the output of the system can be in the 60 GHz range [53]. In this field, much study has been done recently on optical transmission of UWB signals [54-78], in particular for WPANs applications. Different formats for optical transmission, like Impulse Radio (IR) or MB-OFDM, have been compared [79]. Some simplified optical transmitters and receivers of an UWB signal, with direct photonic conversion techniques, have also been proposed. They include optical detection and regeneration of the optically generated 24- GHz UWB signal with a bandwidth of 4 GHz at a data rate of 250 Mb/s after 3-m long transmission in the air. This technique uses an EOM modulated at 24 GHz, and works with a Double Side Band Suppressed Carrier (DSB-SC) [80].

For a UWB signal at higher frequency, one first attempt at up-conversion was made at 40 GHz with cascaded modulators and a DSB-SC method for frequency up-conversion of a UWB monocycle signal with a total conversion gain of -56 dB [81] including optical link loss. Generation of a 60 GHz UWB multi-band MB-OFDM signal over fiber by up-conversion using cascaded EOMs has been demonstrated also [82]. Since most commercial modulator bandwidths are limited to the 50 GHz range, 60 GHz applications require finding another way to transmit at that frequency. The above technique, with suppression of the optical carrier (DSB-SC), allows the conversion of the IF signal at $2f_{L0}$ in the 60 GHz range, as shown in Figure 5, and exceeding the EOM bandwidth limitation. In that experiment, the first EOM was biased in a linear regime and modulated by one UWB-OFDM sub-band of 528 MHz width with a QPSK modulation format and 200 Mbit/s bit rate, centered at frequency $f_{RF} =$ 3.432 GHz. This frequency corresponds to the UWB-MB-OFDM sub-band. The second EOM operated at the minimum transmission point for purposes of optical carrier suppression and was driven with a LO at frequency $f_{LO} = +30$ GHz. The Conversion Gain (CG), as defined earlier in this section, is here of $-30$ dB for an LO power of $+15$ dBm. This value takes into account a gain of 20 dB obtained by amplification at the output of the photodiode. Therefore, CG would be of only -50 dB without this amplification. But this low value also includes the optical insertion loss of each modulator, which is of -4 dB to -5 dB optical, represents -8 to -10 dB of electrical loss at the photodiode output for each modulator, and -20 dB for the two cascaded modulators. If we remove this loss from the CG value of -50 dB, a conversion loss of -30 dB is obtained by this method.

Figure 5a shows the QPSK modulated input signal, while Figure 5b shows the two up-converted sidebands and the signal at frequency $2f_{LO} = 60$ GHz.

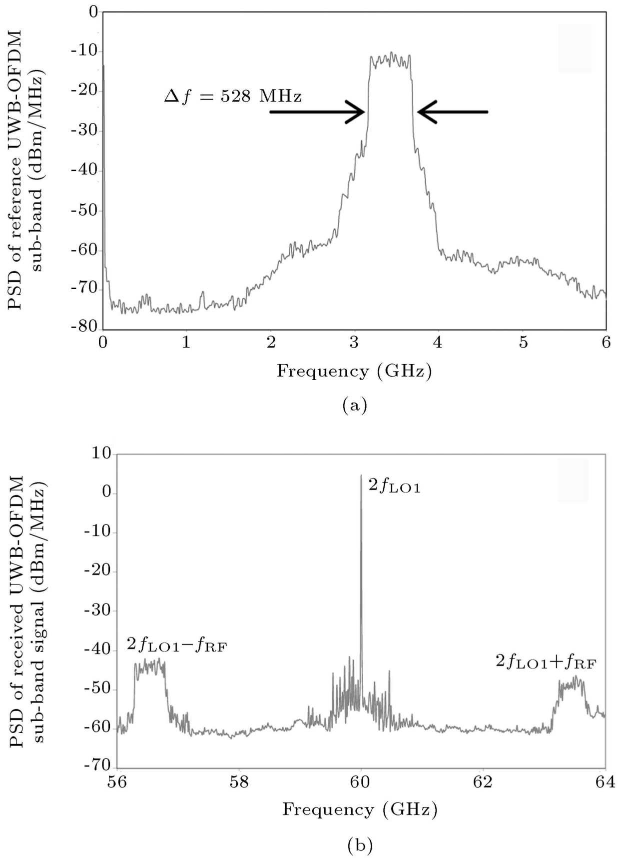


**Figure 5.** Measured spectrum of the first UWB-OFDM sub-band (a) and after up-conversion at 60 GHz (b).

To avoid a chromatic dispersion effect and undesired mixing products, a Fiber Bragg Grating (FBG) optical filter with a suitable rejection profile of +30 dB over 4 GHz spacing can filter out both the 60 GHz signal and one sideband [83].

Error Vector Magnitude (EVM) measurements are often used to evaluate the performance of RF modulated systems [84-87]. For powers, $P_{\rm LO} = +15$ dBm and $P_{\rm RF} = +9$ dBm, an EVM rms of 12.6% at 60 GHz has been obtained by the above system of cascaded external modulators. This corresponds to a BER below $10^{-9}$, which is in compliance with standard requirements [82].

## One Single Optoelectronic Device with Two LO and IF Modulations

Both Distributed Feedback (DFB) laser diodes and VCSELs can be modulated in the 10 GHz frequency range [88-92], and used as up-converters. In that case, the two LO and IF signals modulate the current injected in the laser.

Up conversion, with both directly modulated low-cost multimode 850 nm and single mode 1550 nm VCSEL's, has been demonstrated within the ISIS and UROOF projects [4]. With multimode VCSEL, up-conversion of the triple band UWB OFDM signal composed of time frequency codes TFC5, TFC6 and TFC7 has been demonstrated from UWB band group 1 to band group 3 [93], while it is possible to up-convert the signals all over the UWB bandwidth from 3.1 GHz up to 10.6 GHz. This was based on the third order nonlinearity of a multimode 850 nm VCSEL. The EVM after up-conversion was 20% to 25%, while the back-to-back, without up-conversion, EVM value at the transmitter was 19%. The conversion gain CG was of the order of -22 dB [93].

With single-mode VCSEL, an experiment for up-converting an IR-UWB monocycle was also realized. The feasibility of up-converting the monocycle, while retaining a high resemblance, was demonstrated [33] for lengths of single mode fiber connected to the laser up to 100 m. The spectrum is shown in Figures 6a and 6b, respectively, before and after up-conversion with $f_{\rm LO} = 8.5$ GHz, equal to the relaxation frequency of the VCSEL, for a better conversion gain [35].

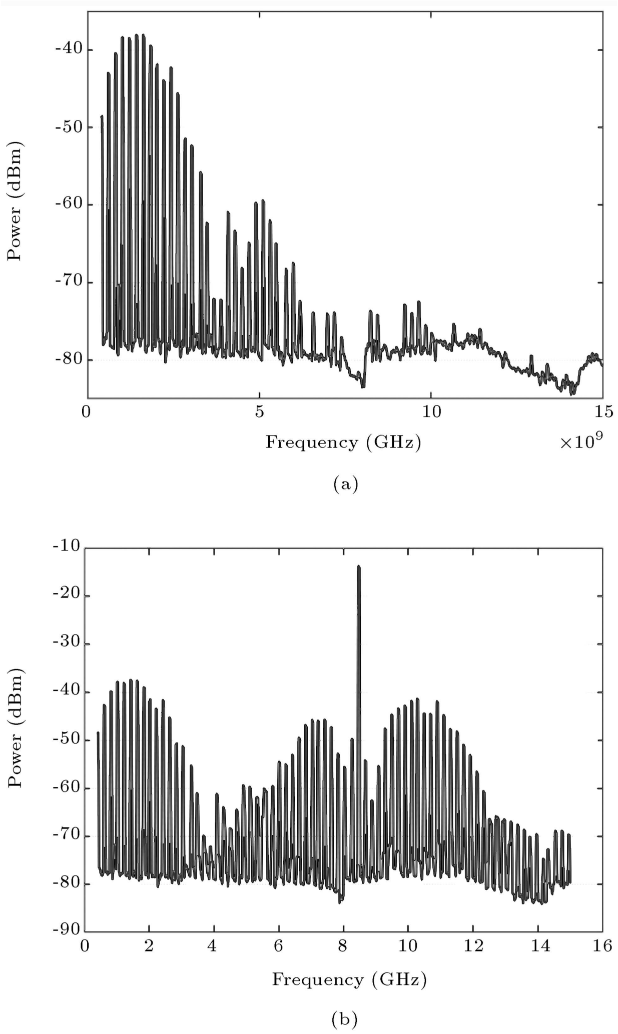


**Figure 6.** Spectrum of the monocycle in the baseband before (a) and after (b) up-conversion.

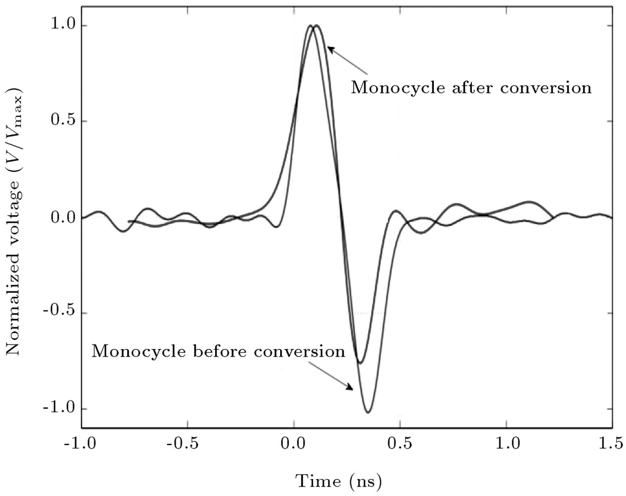


**Figure 7.** Monocycle before and after up-conversion to 8.5 GHz using a single-mode VCSEL.

A monocycle before transmission and the same monocycle up-converted to 8.5 GHz and, subsequently, being down-converted to the baseband for purposes of measurement are shown in Figure 7.

Waveforms of the UWB monocycle signal, before and after frequency up-conversion, are quite similar.

For purpose of comparison between direct transmission and up-conversion with a single optoelectronic device, a unique EOM device has been utilized at the same frequency [94].

The EOM was biased in either a linear (for simple transmission) or non-linear regime (for up-conversion) and was used to realize both distributions of Multi-Band-Orthogonal Frequency Division Multiplexing (MB-OFDM) UWB signals. An all-optical frequency up-conversion of a UWB-OFDM sub-band was demonstrated at around 10 GHz, while this technique could also be applied to the MMW bands, with bandwidth limitation due to the PFD and EOM. Results have shown a low penalty induced by the optical mixing process and enhanced performance of an up-converted MB-OFDM sub-band compared to direct transmission. This is due to reduced optical noise and, consequently, reduced detected shot-noise on the PD, since the EOM biased at a minimum of transmission for mixing purposes has very low optical output power. The optimal conversion gain of this technique is of the order of -45 dB (without amplification) for a LO power of 20 dBm [94].

## Use of Optical Non Linearity

All-optical up-conversion, using cross-gain modulation in Semiconductor Optical Amplifiers (SOA), has been demonstrated [37,38]. This benefits from cross-gain modulation (XGM) in the SOA where a pump wavelength is used to saturate the SOA along with a counter or co-propagating wavelength. The LO signal wavelength can be separated from the IF signal wavelength, and at least one of them must be within the SOA optical gain range. Therefore, a tunable laser source must be used to adjust the wavelength. The double sideband suppressed carrier modulation method with an EOM biased at a minimum of transmission is necessary for the optical carrier supporting the LO signal. For IF and LO powers of around -10 dBm, an optimum conversion gain of -20 dB is obtained.

The SOA photonic up-converter has high conversion efficiency, a LO frequency limited to that of the EOM and high-speed PD, and has a wavelength range compatible with that of the SOA. However, since the SOA operates in saturation, non linear distortion must be studied. The Spurious-Free Dynamic Range (SFDR) is maximum when the IF wavelength is at the SOA gain peak [37], while the measured SFDR is not very high compared to conventional electrical mixers.

## Comparisons Between Optical and Opto-Electronic Techniques for Mixing

Comparisons of up conversion solutions, based on SOA with XGM, and directly modulated DFB or VCSEL's with non-linear functions have been investigated in ISIS [4]. The DFB was the optical source driving the SOA, replacing the tunable laser, as described earlier. The DFB is modulated by the IF data, while an EOM is modulated by the LO signal. Electrical mixing with the VCSEL directly modulated by both LO and IF signals, was undertaken, as described in the previous section.

Under the same conditions for all cases, for purposes of comparison, a 10 MSymb/s QPSK signal; on a $f_{\mathrm{IF}} = 1.1$ GHz carrier was up-converted to 3.1 GHz using a 2 GHz LO tone. The IF input power was only -10 dBm due to the much lower current range of the VCSEL compared to the DFB, and a single operating power for the LO power of 6 dBm was chosen to provide optimum performance.

Figure 8 shows the resulting r.m.s. EVM on the converted 3.1 GHz channel for the three cases: optical mixing based on XGM and tunable VCSEL or XGM with DFB and finally electrical mixing with a single-mode VCSEL.

It can be seen that the technique using the VCSEL has performance benefits and demonstrated both a superior EVM performance as well as operation with lower signal powers. The optical techniques using the SOA show an acceptable but degraded performance. They do, however, provide potential operation benefits, in particular from options for remote operation and the ability to reuse the LO to up-convert a number of IF signals produced by low frequency sources.

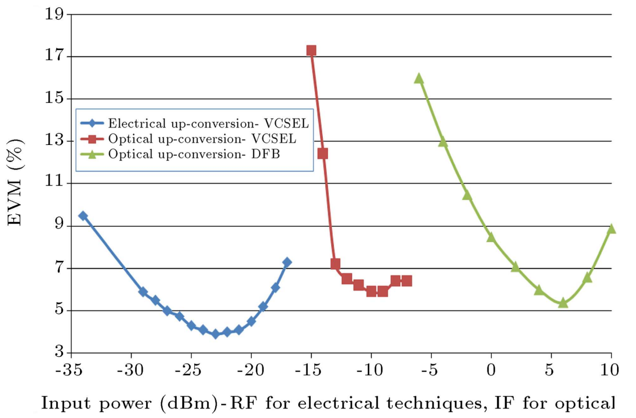


**Figure 8.** Comparisons of EVM after up conversion at 3.1 GHz, with techniques employing an SOA+ tunable source or SOA+DFB laser diode ("optical") and a VCSEL ("electrical").

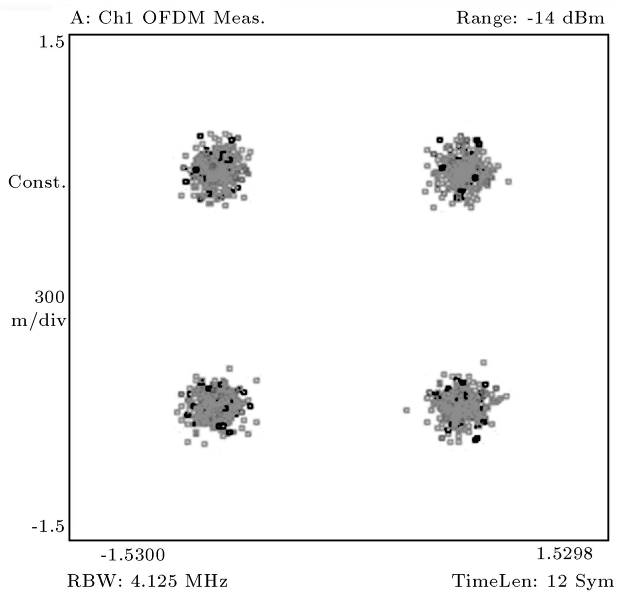


**Figure 9.** Constellation of a QPSK-OFDM signal converted to 60 GHZ and further down-converted by an electrical mixer to an intermediate frequency of 400 MHz.

## Up Conversion with a Photo-Detector

Simultaneous photo-detection and up-conversion can be done by a simple p-i-n photodiode (PD) [26,43,95,96]. In this context, optical up-conversion of a 3.4 GHz bandwidth UWB monocycle has been successfully demonstrated in the 10 GHz band showing good performances in terms of conversion loss and available bandwidth [96]. The up-converted monocycle waveform and spectrum are not affected by the mixing process. With a LO power of 7 dBm, CG has been evaluated at -41 dB including all optical link losses. However, when removing the optical link, an intrinsic loss of -35 dB after linear photo-detection, this conversion gain would be as low as -6 dB. In the 10 GHz frequency range, electrical mixers show a typical conversion loss as low as -4 dB, which is slightly better. However, in MMW bands, electronic mixers integrate high cost electronics and conversion loss increases dramatically, therefore, microwave-photonics mixing can be very attractive. A UWB signal has been successfully up-converted on a 60 GHz frequency carrier [43]. Figure 9 shows the resulting constellation of the QPSK OFDM signal, presenting a bandwidth of 528 MHz up converted in the 60 GHz band, and further down-converted electrically around an intermediate frequency of 400 MHz to fall into the 6 GHz bandwidth of the oscilloscope. The constellation does not show any distortion. The EVM has also been evaluated as being less than 10% after optical up-conversion. This is a very good result, since, according to the ECMA standard [56], EVM lower than 20% guarantees Bit Error Rates (BER) lower than $10^{-10}$ after code correction, which is assumed to be error free transmission.

A new method has been proposed for mixing with PD called optical-microwave double mixing. It utilizes a photodiode and an EOM with two effects: a direct and an indirect mixing process of the modulated optical signal and the microwave signal [95]. An optical carrier with a RF externally modulated signal is applied to a P-I-N photodiode. By a proper embedding circuit in the photodiode, the detected signal is reflected back into the nonlinear EOM device and is then mixed again with the microwave signal, which is a kind of resonant enhancement procedure. The CG is then 10-15 dB higher than the one involving a simple p-i-n mixing without resonant enhancement [95].

Phototransistors have a further advantage over photo-diodes; they act as photo-detectors and amplifiers as well [97-100]. Their non-linear behavior can be exploited for microwave-photonics mixing [3]. Since the photo-HBT has the highest optical coupling efficiency among different photo-transistors [97], can be easily integrated with an amplifier [98] and has low frequency noise [99], this device is attractive for microwave-photonics links. Mixing reported experiments [100] use two photo-HBTs, where one transistor self-oscillates is optically injection locked and feeds, in turn, a second HBT, which serves as an opto-electronic mixer. Analog and digital modulations were demonstrated and the characteristics were found to be better than the corresponding ones in the single HBT case [100]. The two-transistor configuration allows good isolation between the LO carrier and the IF modulated signal. Under an illuminating power of -10- to -3 dBm, the up-converted spectrum of the 30- GHz carrier modulated at 300 MHz exhibited a CG of -16 dB for a modulating input power ranging from -40 to -26 dBm and LO power of -10 dBm.

Experiments have been reported in [3] with a

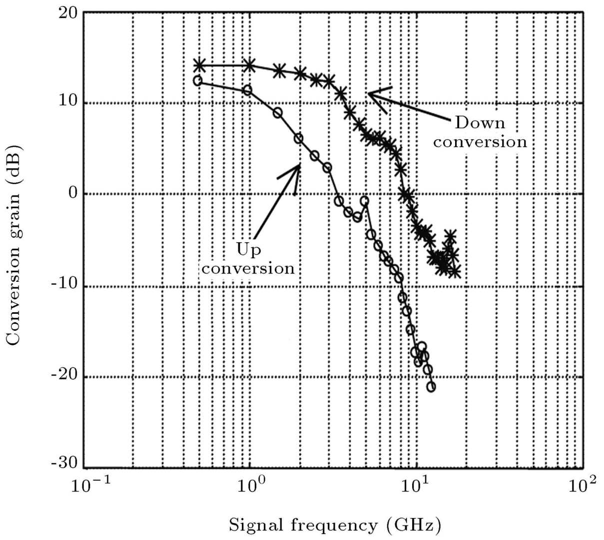


**Figure 10.** Intrinsic conversion gain in a phototransistor as function of IF frequency (after [3]).

unique photo-HBT; results are shown on Figure 10. A DFB laser operating at 1550 nm was externally modulated by an RF source and the optical modulated signal was amplified by an Erbium Doped Fiber Amplifier (EDFA) before being focused onto the optical window of the HBT.

In both down- and up-conversion experiments, with results shown in Figures 10, LO and IF signals were applied; one to the EOM and the other to the HBT base in the range of 0.5-20 GHz, while keeping the separation between them at 500 MHz. The LO power was of -10 dBm. An intrinsic conversion gain is a useful figure of merit for microwave-photonics mixing [3,100].

The intrinsic conversion gain, $G_{\text{int}}$, is defined as the ratio of the output power ($P_{\text{down}}$, $P_{\text{up}}$ for down- and up-conversion) to $P_{\text{prime}}$, the primary photo detected RF power. $P_{\text{prime}}$ is the photo induced RF electrical power detected by the base collector junction without amplification. Figure 10 shows that the conversion gain of the down-conversion process is higher than that of the up-conversion case for all frequencies. The conversion cut-off frequency (defined as the frequency where the intrinsic conversion gain is 0 dB) was 9 GHz for the down-conversion process and $\sim$ 4 GHz for the up-conversion process. The intrinsic conversion gain is high for a frequency below cut-off; this is the main advantage of this technique and can be explained by intrinsic amplification.

## COMPARISONS

Although all techniques described above have their own specificity in terms of system architectures, which require remote or collocated IF and LO inputs, the following Table 1 gives some comparisons of performances based on experimental results as reported here and on theory. Special care must be taken to not take into account RF amplification at the RF output, for an equal basis of comparison.

Conversion gain CG is indicated in Table 1, but values depend on the optical power injected also. Mixing with HBT and LD seems the most efficient in terms of conversion gain CG, but suffers from limited bandwidth. Mixing with cascaded EOMs has a high loss, but allows one to double the frequency and offers a better LO/IF isolation.

**Table 1.** Comparison of different solutions for microwave-photonics mixing under specific conditions.

| **Solutions** | **Unique EOM** | **Unique LD** | **2 Cascaded EOMs** | **Cascade LD+Phase Modulator** | **P-I-N Photodiode** | **HBT** |
|---|---|---|---|---|---|---|
| Conversion gain CG (dB) | -45 | -22 | -50 (without amplification) | | -41 | -16 |
| LO power needed (dBm) | 20 | 1-6 | 15 | 18 | 7 | -10 |
| IF frequency limit (commercial devices) | 50 GHz (can be doubled) | 10 GHz | 50 GHz (can be doubled) | 10 GHz | 50 GHz | 4-9 GHz |
| Rejection of fundamentals | Yes | No | No | Yes | No | No |
| LO/IF isolation | No | No | Yes | Yes | Yes | Yes |

## CONCLUSIONS

Microwave-photonics has demonstrated the capability to transmit and process wide band signals in the microwave and millimeter-wave regions.

We have described various methods and research results in photonics microwave mixing, mainly for radio-over fiber applications. These are based on both direct and external modulation, photo-detection, and the use of single-mode and multimode fiber, for the support of existing and emerging communication networks. Novel architectures for both analogue and digital signal processing are possible, and are more and more attractive, since the frequency and dynamic response of optoelectronic components have improved in the past decade and are now competitive in regard to pure electronics.

Implementation of several photonic components and systems with high efficiency for microwave mixing is necessary in their applications to wireless, security and radar systems. The results in this paper show that it is possible to up- or down-convert with high efficiency microwaves and complex digital signals. The conversion gain depends on many factors like available optical and local oscillator power, and architecture with remote or close inputs to the microwave-photonics mixer.

With a continuously evolving market in broadband and high capacity communications, many other solutions will probably emerge in the future.

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