Microwave-Frequency Conversion Methods by Optical Interferometer and Photodiode

Ghislaine Maury, Attila Hilt, Tibor Berceli, *Fellow, IEEE*,
Beatrice Cabon, *Member, IEEE*, and Anne Vilcot, *Member, IEEE*

***Abstract*— Frequency conversion in fiber-optic systems like subcarrier multiplexed (SCM) systems is now to be used in many applications for both digital and analog signals. The performance of two different optoelectronic configurations, both used for frequency conversion in the microwave frequency range, are compared here. In the first case, mixing is achieved by a Mach–Zehnder (MZ) interferometer, while in the second case, photodiode mixing is presented. Experimental investigations are presented at the optical wavelength of 1.3 μm. In both cases, promising results have been achieved.**

***Index Terms*—Fiber-optic links, frequency modulation, generation of optical mixing, interferometers, photodiode mixing.**

I. Introduction

RECENTLY, fiber-optic links have been investigated by several authors for the transmission and distribution of microwave and millimeter-wave signals. For further signal processing, frequency conversion is necessary in several applications, e.g., in wireless distribution of optically received signals [1]. Efficient mixing methods are required for this purpose to simplify the complexity of the system.

The traditional solution employs electronic mixers for the frequency conversion of detected optical signals which are modulated by RF signals. However, by adding or benefiting of the nonlinearities in the optical link, the frequency conversion can be finished eliminating electronic mixers. Two alternative methods for conversion are presented and compared in this paper.

II. Mixing with UMZ/PD

A. Principle

In the first case, the optical system used for microwave mixing is a distributed feedback (DFB) laser diode (LD) directly modulated by two microwave frequencies, f_1 (e.g., $f_{\rm LO}$ corresponding to the LO signal) and f_2 (in this case, $f_{\rm RF}$), followed by an unbalanced MZ (UMZ) and a photodetector (PD) [2]. The system is shown in the upper portion of Fig. 1.

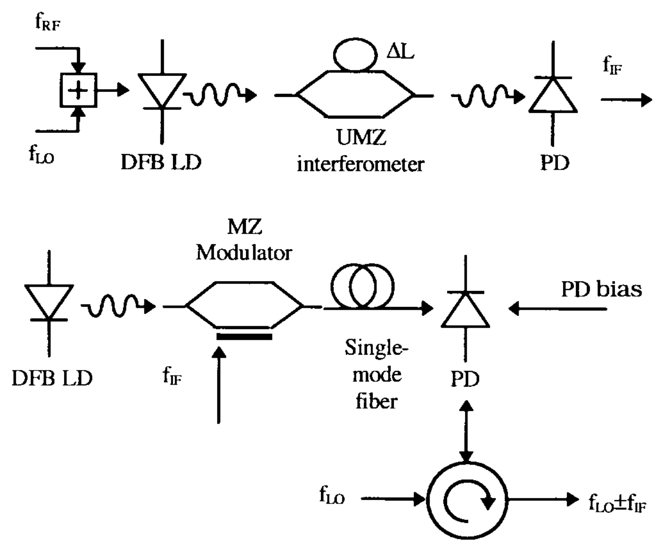

Fig. 1. Optical systems used for microwave-optical mixing.

The basic principle is the nonlinear (sinusoidal) intensity response of the UMZ interferometer/PD combination as a function of the frequency of the optical field [3]. Direct modulation generates FM, which is then converted to AM using the UMZ interferometer working in the coherent regime. The PD detects the optical intensity which is a quadratic function of the optical field, so frequency mixing is obtained. The originality of our solution is the use of a passive optical device inserted in the optical link which generates mixing with better conversion than classical solutions using active MZ modulators.

Considering a linear LD operating regime and neglecting AM, the intensity at the output of the interferometer, with delay time τ between both arms is given by

$$I(t) = \frac{E_0^2}{2}\Big\{1 + V(\tau)\cos\Big[2\pi\nu_0\tau + \beta_1 \sin\Big(\omega_1\frac{\tau}{2}\Big) \cdot \cos\Big(\omega_1\Big(t+\frac{\tau}{2}\Big)\Big) + \beta_2 \sin\Big(\omega_2\frac{\tau}{2}\Big) \cdot \cos\Big(\omega_2\Big(t+\frac{\tau}{2}\Big)\Big)\Big]\Big\}$$

where $\beta_{1,2}$ is the FM index, $\omega_{1,2}$ is the angular modulation frequency, and $V(\tau)$ reflects the loss of coherence between

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G. Maury, B. Cabon, and A. Vilcot are with the Laboratoire d'Electromagnétisme, Micro-ondes et Optoélectronique (LEMO), ENSERG, Institut National Polytechnique de Grenoble (INPG), F-38016 Grenoble, Cedex 1, France.

A. Hilt is with the Laboratoire d'Electromagnétisme, Micro-ondes et Optoélectronique (LEMO), ENSERG, Institut National Polytechnique de Grenoble (INPG), F-38016 Grenoble, Cedex 1, France and BME-MHT, Technical University of Budapest, H-1111 Budapest, Hungary.

T. Berceli is with BME-MHT, Technical University of Budapest, H-1111 Budapest, Hungary.

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the electric field in both arms of the interferometer. In the coherent working regime $V(\tau) = 1$ and in the incoherent regime $V(\tau) = 0$.

As can be deduced from the equation, in the coherent working regime, when the interferometer is balanced on a *bright* or *dark* fringe, i.e., when $\cos(2\pi \upsilon_0 t) = \pm 1$ (condition 1), the resulting intensity is generated at harmonics and intermodulation products of even order (of the form $nf_1 \pm mf_2$ with $n + m \in 2Z$) and, in particular, at the mixing frequency $f_{\rm IF}$. Condition 1 is then the first condition to obtain the best mixing at frequency $f_{\rm IF}$.

To be optimized, the output spectrum of the optical intensity must exhibit the maximum power of the mixing frequency and the minimum power of the input frequencies. This second condition (condition 2) is fulfilled when

$$f_1 = (2k+1)\frac{\rm FSR}{2}$$

and

$$f_2 = (2k'+1)\frac{\rm FSR}{2}, \quad (k, k') \in N^2$$

where ${\rm FSR} = 1/\tau = {\rm c}/({\rm n_{eff}}\Delta{\rm L})$. Therefore, $f_2 - f_1$ must be as close as possible to a multiple of the free spectral range (FSR). For given input microwave frequencies, the ΔL must be chosen to match these two conditions.

The response at the PD output is periodic with the input frequencies, which means that the device does not optimally work for all frequencies but for particular frequencies in any frequency range. Within a period, the 3-dB bandwidth approximates FSR/2. However, in some applications, it is advantageous since the UMZ acts as a microwave filter too.

B. Simulation Results

By Fourier transform, we can calculate the power of the different frequency components in the PD current in the general case with AM, as a function of different parameters. We have simulated an LD with linewidth enhancement factor $\alpha = 5$, threshold current $I_{\rm th} = 15$ mA, and biased at $I_0 = 22$ mA. The optical power coupled in the interferometer is assumed to be 1 mW. ΔL is calculated so that the ${\rm FSR} = 1$ GHz.

The conversion loss has been defined independently from the electrical–optical (E/O) and optical–electrical (O/E) conversions inherent in an optical link. It is then the difference between the power of the IF component with the configuration including the UMZ in the optical link, and the power at frequency $f_{\rm RF}$ detected by the PD without inserting the UMZ.

This loss has been calculated as a function of $P_{\rm LO}$, with two optimized frequencies ($f_1 = 10.5$ and $f_2 = 11.5$ GHz). It was also assumed that the interferometer worked in the coherent regime and at maximum transmission (ΔL is, in this case, equal to $\Delta L_{\rm opt}$). The results are plotted in Fig. 2. As can be easily shown in the simplified case with AM neglected, the calculations exhibit in this case an optimal $P_{\rm LO}$ for which the conversion is maximal and is even a gain. The variation of the conversion loss versus the deviation from the maximum transmission $\varepsilon = (\Delta L - \Delta L_{\rm opt})/\lambda$ is also shown. When $\varepsilon = 0.25$, the interferometer works in the linear regime, which is the worst case for mixing. When $\varepsilon = 0.5$, it works at minimum transmission and mixing is optimal like at maximum transmission.

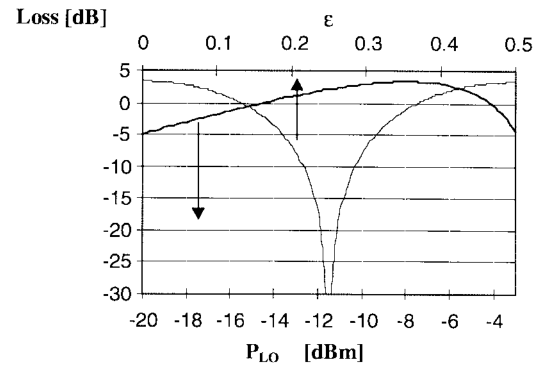

Fig. 2. Variations of the conversion with $P_{\rm RF} = -25$ dBm and for optimized frequencies as a function of $P_{\rm LO}$ and e.

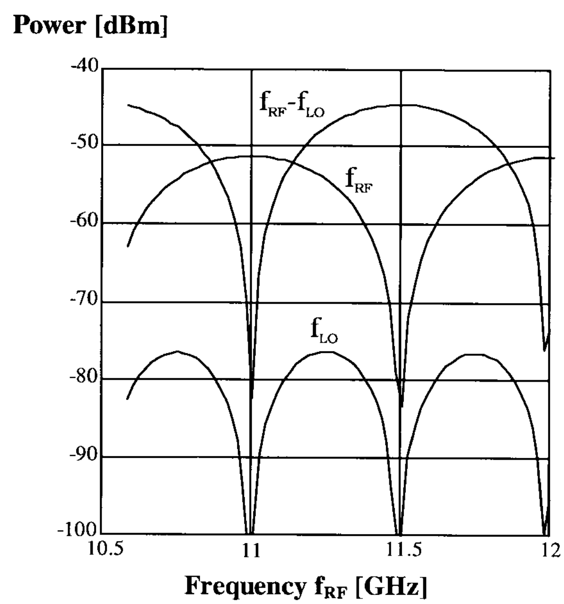

Fig. 3. Power of the frequency components after detection with $f_{\rm LO} = 10.5$ GHz, $P_{\rm LO} = -8$ dBm, $P_{\rm RF} = -25$ dBm.

Fig. 3 exhibits the simulations of the power of the different frequency components at the PD output as a function of $f_{\rm RF}$ varying in a band larger than FSR, with the optimal $P_{\rm LO} = -8$ dBm and $f_{\rm LO} = 10.5$ GHz. It is confirmed that the maximum power of $f_{\rm IF}$ is obtained at $f_{\rm RF} = 11.5$ GHz. For this frequency, the fundamentals $f_{\rm RF}$ and $f_{\rm LO}$ are rejected. More generally, it can be noticed that the mixing frequency can be the sum or the difference of the input frequencies and that these two cases exhibit quite the same power.

In conclusion, simulations confirm the possibility of realizing the mixing function with an UMZ operating at maximum or minimum of transmission. We emphasize that the mixing is not a consequence of the LD nonlinearities. Conversion gain can even be obtained instead of conversion loss if the LD has an important linewidth enhancement factor $(\alpha > 3.5)$, which means a high FM efficiency.

III. Mixing by Photodiodes

A. Photodiode Characterization

In the single PD mixing experiment we used PD94CP-S12 chips, manufactured by Opto Speed. These high-speed p-i-n photodiodes have a waveguide structure similar to that presented in [4]. The active area of the PD is 16 × 16 μm^2. The tapered coplanar transmission line enlarges the metallized contacts to a pitch distance of 150 μm, allowing coplanar probe measurements. Impulse response measurements were performed by the manufacturer. Rise and fall times shorter than 18 ps were obtained, corresponding to a bandwidth greater than 40 GHz.

We characterized the PD chips by frequency-domain measurements up to 20 GHz using an HP 8510B Vector Network Analyzer extended by an HP 83420A LightWave Test Set (LWTS). The LWTS includes a DFB laser emitting at $\lambda = 1.3\,\mu$m and a MZ interferometer modulator.

First, the detection properties of the PD have been investigated by coaxial measurements of PD chips bonded onto connectors. Then the responsivity (O/E conversion) was tested by air-coplanar microwave probe measurements. The responsivity is frequency and bias dependent. In the coaxial configuration there is a roll-off due to the inductance of the bonding wires [5]. The bandwidth obtained by probe measurements was higher than the 20-GHz frequency band of our experimental setup.

B. Principle of Optical-Microwave Mixing

The optoelectronic system explored for optical-microwave mixing is shown below the UMZ/PD system in Fig. 1. The mixing was analyzed based on the dc characteristics at different optical intensities illuminating the device. To achieve good detection, the PD is used in its linear regime where the applied reverse bias is usually several volts [5]. However, even in this regime a noticeable nonlinearity is present at higher light injection levels [6].

Simultaneously injecting a microwave signal at the electrical port of the PD and a modulated optical signal results in the mixing of the two signals. The optimal bias points for efficient mixing and for efficient detection are significantly different (Fig. 4). The mixing process is explained as a result of the nonlinearity of the PD current–voltage relationship. Due to the fact that the characteristics exhibit the maximum nonlinearity in the vicinity of 0 V, it is the optimal operation point for efficient mixing [5], [7]. Nonlinearity of the PD generates several mixing products of the microwave driving signal $f_{\rm LO}$ and of the photo-induced signal $f_{\rm IF}$. By injecting an LO signal $f_{\rm LO} > f_{\rm IF}$, the detected optical signal is upconverted.

Fig. 4 represents the voltage dependence of the detection and of the mixing products at $f_{\rm LO} + f_{\rm IF}$. In this experiment, $f_{\rm LO} = 3$ GHz was used and the light was intensity modulated by $f_{\rm IF} = 150$ MHz. Optimal detection is achieved by high reverse bias and a plateau is observed at bias points $V_{\rm PD} < 0$. In the absence of electrical excitation, the power of the second harmonic was considerably small, taken into account also the

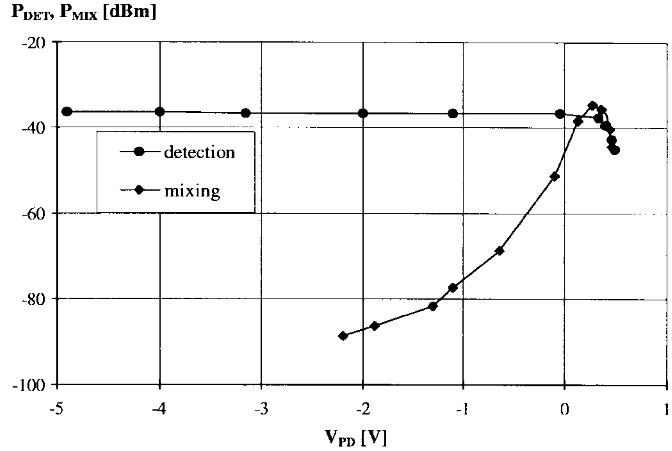

Fig. 4. Voltage dependence of the detected power and of the upper-sideband mixing product.

contribution of the modulator part. However, the most efficient mixing is obtained at a bias close to $V_{\rm PD} = +0.3$ V, having a sharp optimum. The bias dependence of the upconverted signal for a metal–semiconductor–metal PD (MSM-PD) was investigated in [7] where the optimal bias has not presented such a sharp optimum. Conversion loss of the electro-optical mixing process is defined as the ratio of the power at $f_{\rm IF}$ (using the PD in its linear regime as a PD) and of the signal levels at $f_{\rm LO} \pm f_{\rm IF}$ frequencies upconverted by the PD nonlinearity [8]. Varying $P_{\rm LO}$, even conversion gain may be obtained.

IV. Experimental Results for Mixing

A. Experimental Results with UMZ/PD

Measurements have been made with a DFB LD emitting at $\lambda = 1.3\,\mu$m, having an $I_{\rm th} = 13$ mA and a maximal oscillation frequency of 2.5 GHz. The dc-bias current was 22 mA and the optical power coupled in the interferometer was 420 μW.

Reflections at the fiber pigtail facet generate optical feedback in the LD, and thus decrease its coherence length. To operate in the coherent regime as wanted, the UMZ was realized using only two connectorized −3-dB fiber directional couplers. In this case, $\Delta L = 1.6$ cm, which corresponds to ${\rm FSR} = 13$ GHz.

The LO frequency was $f_{\rm LO} = 1.9$ GHz, with a power of −4 dBm. The other modulation frequency, $f_{\rm RF}$ was swept from 2 up to 2.5 GHz and had a power of −18 dBm. Fig. 5 shows the power spectrum of the intensity detected by the PD and measured by a spectrum analyzer. In Fig. 5, the lower sideband of the mixing product, $f_{\rm LO} - f_{\rm RF}$, as well as the third-order intermodulation product, was significantly increased by inserting the UMZ. However, the input frequencies $f_{\rm LO}$ and $f_{\rm RF}$ are not rejected. In fact, to obtain an optimal rejection of the fundamentals, condition 1 should first be fulfilled, which was not the case under the conditions of operation. The relative optical phase shift between the two arms is very sensitive to ambient variations, and during the experiments the operating regime continuously varies between minimum and maximum transmission including the quadrature. Secondly, the closer f_1

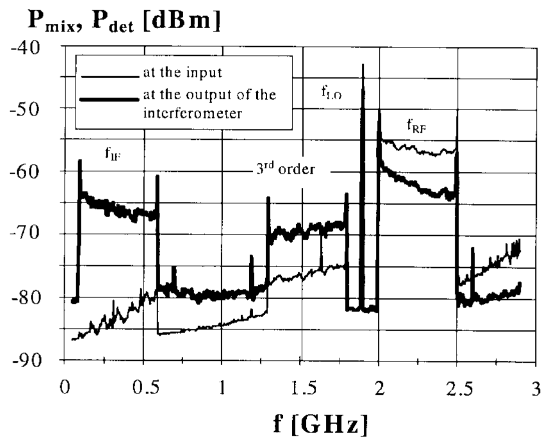

Fig. 5. Power spectra of detected signals with and without UMZ.

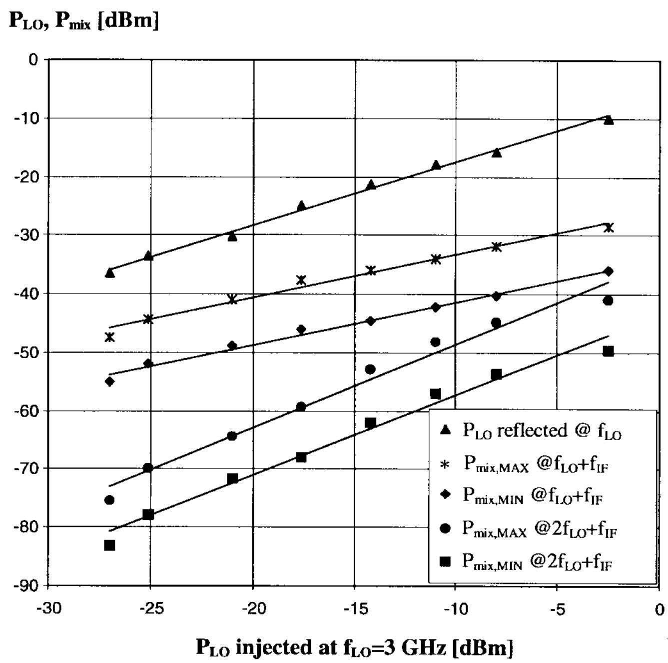

Fig. 6. Levels of first and second harmonic mixing as a function of $P_{\rm LO}$, $m = 25\%$ (MIN), and $m = 75\%$ (MAX).

would be to $\text{FSR}/2 = 6.5$ GHz, the larger the rejection would be, and here $f_1 = f_{\rm LO} = 1.9$ GHz (limitation due to the LD).

B. Experimental Results with PD

Investigating the frequency conversion, a PD bonded onto a connector by parallel gold wires was illuminated by the DFB LD via a monomode fiber. The LO signal was fed to the PD through a wide-band circulator or a directional coupler separating the LO input and the RF output. No amplifier was used to avoid additional nonlinearities.

Fig. 6 shows the first and second harmonic mixing of $f_{\rm IF}$ and $f_{\rm LO}$ frequencies as a function of the injected LO power measured by a spectrum analyzer. The LO frequency was $f_{\rm LO} = 3$ GHz while the optical intensity was modulated by $f_{\rm IF} = 150$ MHz. The driving LO signal reflected at the PD is shown as well. A slight saturation effect is observed at $P_{\rm LO}$ close to 0 dBm and a proportional increase of the mixing products is shown for greater optical modulation depth (OMD). Results of Fig. 6 demonstrate the interest of exploring the generation of second or higher harmonics for mixing purposes. It can find applications in systems where the LO signal is received from a remote site. Using subharmonically pumped mixing, only the subharmonic of the LO signal has to be transmitted.

Different LO frequencies have been applied in the passband of the circulator [5]. Double-sideband (DSB) upconversion is presented in Fig. 7. The frequency of IM was swept from 45 to 850 MHz and $f_{\rm LO}$ was 8 GHz. The decay in the first-order mixing products with increasing modulation frequency is rather small. Modulating the optical signal by higher frequencies, the response was quite flat up to 1.5 GHz. The applied bias was optimized for mixing. The influence of $P_{\rm LO}$ is demonstrated at two modulation depths: $m = 25\%$ (MIN)

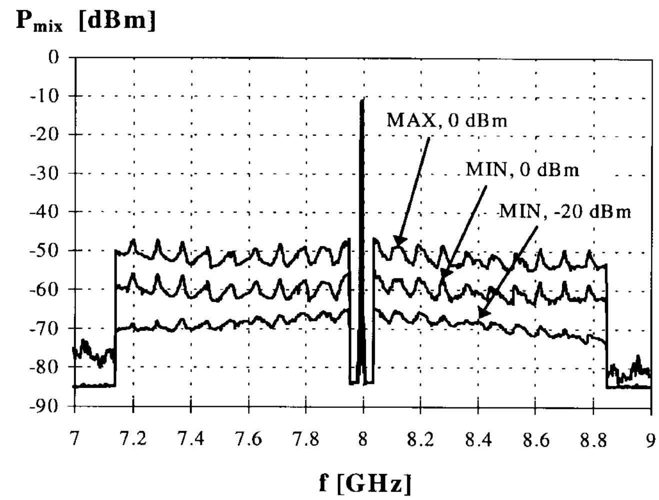

Fig. 7. Upconverted signal by PD mixing, $f_{\rm LO} = 8$ GHz, $P_{\rm LO} = 0, -20$ dBm, $f_{\rm mod} = 45, \cdots, 850$ MHz.

TABLE I
COMPARISON OF THE TWO METHODS

COMPARISON OF THE TWO MIXING METHODS	UMZ / PD MIXING	PD MIXING
principle of operation	use of a passive optical device (UMZ)	nonlinearities of the PD
possible applications	- downconversion of RF signals for optical transmission (e.g. received in wireless systems), - SCM systems (emission side)	- wireless distribution of optically received signals (upconversion), - SCM systems (reception side), - signal analysis (downconversion)
frequency dependence	periodic (period is a function of ΔL)	flat response (if there is no mismatch)
bandwidth limitations	limited by LD and PD bandwidths and not by the UMZ	bandwidth of PD and its external circuit (circulator or coupler)
conversion gain/loss	gain is theoretically available	
conversion loss vs. P_{LO}	curve with optimum	curve with saturation
rejection of the fundamentals	complete rejection if mixing is optimal (Fig.3)	only by external filtering
generation of harmonics	yes	subharmonically pumped mixing

and 75% (MAX). The periodic ripple on the measured curves is mainly caused by the imperfect impedance matching of the PD to the coaxial 50-Ω lines.

At low levels, the power of the mixing products is proportional to the OMD and to the LO power ($P_{LO} < -5$ dBm). At higher levels, a saturation effect is observed ($P_{LO} \cong 0$ dBm). However, the frequency behavior in Fig. 7 is dependent neither on the variations of the OMD nor those of the LO power.

V. Comparison of the Two Methods

The principle of frequency conversion is different in the presented methods. In the first case, the f_{LO} and f_{RF} signals are optically converted by FM, mixed by UMZ, and transmitted. Applications are at the emission side of a fiber-optic link. In the second case, mixing is realized at the reception of the optical link. Only the frequency f_{IF} is transmitted by optical IM. In Table I, the two solutions are compared.

VI. Conclusion

Optical-microwave mixing was investigated for both up and downconversion using two different approaches, one with a high-speed p-i-n PD and the other with an UMZ/PD combination. Both solutions permit the mixing of microwave frequencies in optical links, which is a new approach compared to the traditional solutions using electronic mixers. Efficient frequency conversion was measured in both cases. The frequency dependence of the converted signals has been investigated by simulations and measurements. The main limitations of the proposed solutions are only due to the bandwidth of the components used in the E/O and O/E conversions.

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Ghislaine Maury received the grade of engineer in telecommunications from Ecole Nationale Superieure des Télécommunications, Paris, France, in 1995, and the Diplóme d'Etudes Approfondies in electronics from University Paris VI, Paris, France, in 1995. She is currently working toward the Ph.D. degree at the Laboratoire d'Electromagnétisme, Micro-ondes et Optoélectronique (LEMO), ENSERG, Institut National Polytechnique de Grenoble (INPG), Grenoble, France.

Attila Hilt received the electrical engineering degree from the Technical University of Budapest (BME), Budapest, Hungary, in 1990. He is currently working toward the Ph.D. degree at the Laboratoire d'Electromagnétisme, Micro-ondes et Optoélectronique (LEMO), ENSERG, Institut National Polytechnique de Grenoble (INPG), Grenoble, France, and at the Microwave Telecommunications Department of BME.

Since 1989, he has been with TKl, Research Institute for Telecommunications, Budapest, Hungary, where he was involved in the development of microwave and millimeter-wave circuits and systems.

Tibor Berceli (SM'77–F'94) was born in Budapest, Hungary. He received the electrical engineering degree from the Technical University of Budapest (BME), Budapest, Hungary, in 1951, and the Candidate of Technical Science (Ph.D.) and Doctor of Technical Science degrees from the Hungarian Academy of Sciences, Budapest, Hungary, in 1955 and 1965, respectively.

In 1951, he joined TKI, Research Institute for Telecommunications, Budapest, Hungary. Since 1962, he has held a part-time job at the Technical University of Budapest, where he is currently a Professor of electrical engineering. He has been a Visiting Professor at Polytechnic Institute of Brooklyn (1964), University College London and Drexel University (1988–1989), Technical University of Hamburg (1991), Osaka University (1992), and Technical University of Grenoble (1994). He has authored 96 papers and 6 books published in English, and has presented 62 papers at international conferences. He has investigated surface-wave transmission lines, dielectric waveguides, travelling-wave tube amplifiers, reflex klystron oscillators, several kinds of microwave semiconductor oscillators and amplifiers, parametric circuits, up- and down-converters, and injection-locked oscillators. His present field of interest is the optical–microwave interaction.

Prof. Berceli was chairman of the Organizing Committee for the URSI International Symposium on Electromagnetic Wave Theory in 1986, and conference chairman of the 20th European Microwave Conference in 1990.

Beatrice Cabon (S'93–M'95) was born in France in 1954. She received the Ph.D. degree in microelectronics from Institut National Polytechnique de Grenoble (INPG), Grenoble, France, in 1986.

From 1986 to 1989, she was working with the National Center of Telecommunications (CNET), CNS, Grenoble, France, in the field of CAD and modeling of microelectronic components. Since 1989, she has been an Associate Professor at the National Polytechnic Institute of Grenoble (INPG), Grenoble, France, where she trains engineering students in electronics and microwave engineering. In 1989, she joined the Laboratoire d'Electromagnétisme, Micro-ondes et Optoélectronique (LEMO), ENSERG, Institut National Polytechnique de Grenoble (INPG), Grenoble, France. She is presently head of a research group of optics/microwave interactions and is involved in the optical-microwave interactions with optical control of microwave devices and all-optical circuits for processing of microwave signals. Her research interests have been the modeling of propagation characteristics of various passive superconductive circuits (transmission lines, couplers, filters).

Anne Vilcot, (S'90–M'92), for a photograph and biography, see this issue, p. 1367.