All-Optical Networks as Microwave and Millimeter-Wave Circuits

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Abstract—**In this work we study the use of optical fiber networks to perform microwave processing functions. Theoretical and experimental results are presented in the case of a Mach-Zehnder interferometer network, a Fabry-Perot network, and a combination of the two previous networks. All of these networks are realized with single-mode fiber elements. The use of optical scattering parameters and the graphical representation technique was introduced in our model, which greatly simplified the analysis. A good agreement between modeling and experiment as well as good performances from the microwave point of view are observed.**

I. Introduction

The MERGING of microwaves/millimeter-waves and optics is now a topic of great interest, which opens the door to a new family of optical-based microwave devices and circuits with exciting characteristics. One of the applications of such a topic is the long-distance transmission of both analogue and digital microwave signals by superimposing these on an optical carrier. However, the technological advances in electrical-to-optical (modulation) and optical-to-electrical (detection) conversions today allows one to consider not only the simple optical transmission of microwave signals, but also the optical processing of these signals. Thus, instead of processing the modulating signal before the optical modulation or after its detection (i.e., in the electrical domain), this processing could be made in the optical domain after the modulation. This optical processing is much more interesting at higher modulating frequencies where the wideband processing of microwaves/millimeterwaves is quite difficult. It will be essentially limited by the modulation and detection frequency responses. Nowadays, the direct modulation of the laser diode may be up to 20 GHz (40 GHz for some special structures) and with external modulation it might be 40 GHz while the available detection devices are in the 60 GHz range. For such a processing, the simple optical cable needed for the optical transmission will be replaced by an optical network. Such a technique has already been used to design true time delay-line both in multimode fibers [1] and single-mode fibers [2], [4]. By exploiting the interference effects of the microwave envelopes and/or the optical carriers in a suitable arrangement of some basic optical elements like waveguides, couplers, etc., a variety of desired microwave processing functions could be achieved. Such a configuration used in itself as a "microwave device" offers a perfect isolation between the input modulating microwave signal and the output detected one.

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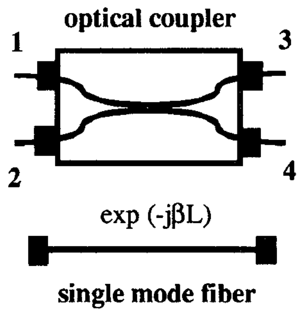

Fig. 1. The two single-mode optical components usually used for optical signal processing structures.

The optical network built only with fiber elements offers the advantage of very low propagation losses and dispersion. However, when dealing with millimeter-wave signal processing, integrated optical networks are of special interest for the realization of short and precise length of the optical delay lines. In this paper, we discuss the performances of short optical networks based on optical fibers in order to design and realize some passive microwave devices for analogue applications. We begin by introducing the techniques used for the theoretical analysis of such networks and then giving the corresponding experimental results showing the validity of the present models.

II. Theoretical Analysis

As presented in the introduction, the microwave behavior is mainly determined by the interference effects of the microwave envelopes and the optical carriers inside the optical networks. Thus a rigorous theoretical analysis must be able to describe the input-output relationship of the modulated optical fields. Such an analysis could be made in the time domain [7] to take into account the noncoherent or the quasi-coherent nature of the propagating light. The main difficulty of the time domain analysis is its high degree of complexity when dealing with large scale optical structures such as ladder networks. The frequency domain analysis based on the optical S-matrix concept is much more convenient for such a case, however the spectral distribution of the optical source must be taken into account in order to calculate the output optical power reaching the photodetector [8].

To many points of view, optical networks can be considered as an extension of traditional microwave circuits and it is possible to extend the well-known S-parameters theory to the

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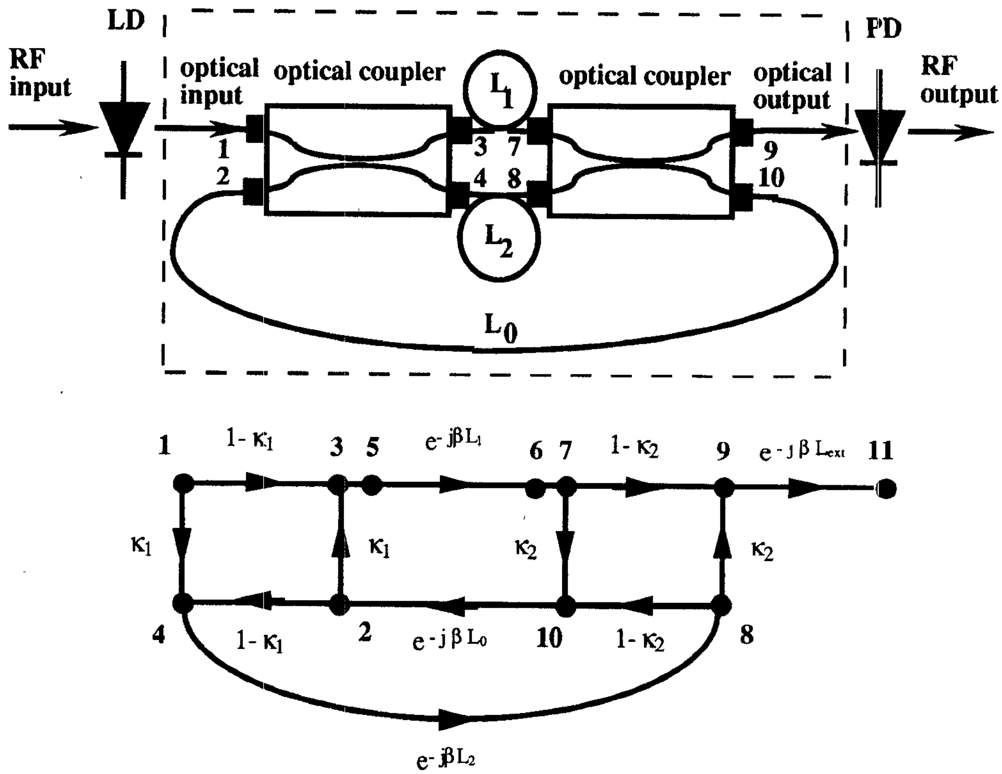


Fig. 2. The Recirculating Unbalanced Mach-Zehnder Interferometer and its corresponding graphical representation.

optical context [3]. However, some specific aspects should be taken into account in optical networks such as the polarization and the coherent properties of the optical signal. Actually, for any single mode all-optical component, we can associate an optical S-matrix that has the similar physical meaning as the microwave S-matrix. This S-matrix is defined in the frequency domain and then it assumes that the propagating signal is a perfect coherent one. On the other hand, even with a perfect coherent optical signal, the optical S-matrix will be different from the microwave one because the single-mode optical component admits in fact two guided modes referring to the two classical polarizations of the optical signals. This means that at each port of the optical component we have to consider two incident signals and two reflected signals. Inside the optical component it may exist a coupling or a power transfer between the two modes or the two polarizations. This may be taken into account by using the Jones calculus for the description of the optical component/network.

The rigorous analysis is necessary when the delay times of the elements is comparable with (or less than) the coherence time of the optical signal used, i.e., when the light carrier interferences can take effect. For the incoherent working regime of the optical signal processing networks, it is well-known that the microwave behavior is dependent only on microwave envelope interference effects. In such a case, the analysis can be greatly simplified and we can consider the propagation of light intensities inside the network rather than optical fields. The basic optical components such as optical couplers and fibers can be considered as lumped elements characterized by their intensity input-output relationships which can be experimentally determined by some methods previously proposed [10], [11]. Thus, the signal flow graph technique [5] can be applied very conveniently to obtain the overall microwave transfer function. The present analysis is based on the assumption of an incoherent optical source. This corresponds to our practical results where the use of a directly modulated laser diode butt-coupled into a single-mode fiber without optical isolator has destroyed the coherence of the light.

The two basic optical components of interest in our study are the single-mode optical coupler and the optical fiber as shown Fig. 1. The intensity input-output relationship of a symmetric, matched optical coupler is a $2 * 2$ matrix given in (1) [3]

$$\begin{bmatrix} I_3 \\ I_4 \end{bmatrix} = \gamma \begin{bmatrix} 1-\kappa & \kappa \\ \kappa & 1-\kappa \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (1)$$

where γ characterizes the total loss and κ is the intensity coupling coefficient. The single-mode fiber can be considered as lossless and dispersion free for a relatively short length L. Thus the microwave envelope of the light intensity which propagates through the fiber will suffer only a phase shift

$$I_{\text{out}} = I_{\text{in}} e^{-j\beta L} \quad (2)$$

where $\beta = \omega_{\text{RF}} n_{\text{eff}}/c; n_{\text{eff}}$ is the effective optical index of refraction and c the light velocity. The physical structures of the Recirculating Unbalanced Mach-Zehnder (RUMZ), the Fabry-Perot Ring Resonator (FPRR) are given Figs. 2 and 3, respectively. When the feedback fiber Lo of the RUMZ is removed (see Fig. 2), the RUMZ becomes simply an Unbalanced Mach-Zehnder Interferometer (UMZ). We will present in detail the theoretical analysis for the case of the RUMZ, which is the most complex structure in our study. For the two

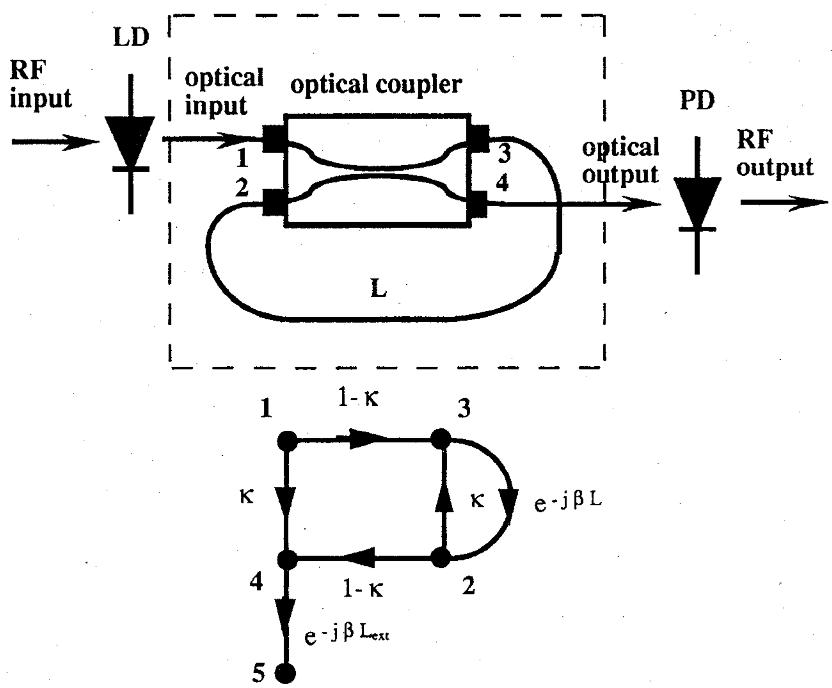


Fig. 3. The Fabry-Perot Ring Resonator and its corresponding graphical representation.

other configurations, only the results will be given. The latter are straightforward obtained using the procedure developped for the RUMZ.

A. Analysis of the Recirculating Unbalanced Mach-Zehnder

In this analysis the couplers are assumed lossless, i.e. $\gamma = 1$ and the coupling coefficients are κ_1 and κ_2, respectively. The corresponding graphical representation that characterizes the structure is given Fig. 2. In order to get the overall microwave frequency response $H(\omega_{\rm RF})$ we calculate the intensity relationship between the input and the output nodes i.e. between the node (11) and the node (1). In our experiments, the optical network under study is connected to the light source and the photodetector through two external single-mode fibers. These fiber lengths will affect the microwave frequency response by an aditionnal phase shift. Therefore, we introduced an external fiber of length $L_{\rm ext}$, which is the total length of the two external fibers in order to take into account these fiber connections.

To solve the above signal flow graph, the well-known Mason's rules were applied [5]. These rules can be stated as follows:

$$G_{ij} = \frac{\sum_{k=1}^{N} P_{ij_k}\Delta_{ij_k}}{\Delta} \tag{3}$$

where G_{ij} is the total gain between the node i and the node j. P_{ij_k} denotes the individual gain between the node i and the node j following the kth path. Δ is the graph determinant which is evaluated by $\Delta = 1-$ (sum of all loop gains existing in the graph) + (sum of all gains products of 2 nontouching loops) $-$ (sum of all gains products of 3 nontouching loops) $+\cdots$.

Δ_{ij_k} is called cofactor of the kth path. It can be evaluated by the same way as for Δ after the removing of all the loops touching the kth path.

For the graph given Fig. 2, between the node (1) and the node (11), there are two possible optical paths and two optical loops

$$\begin{aligned} P_1 &= (1)(3)(7)(9)(11) \\ &= e^{-j\beta L_{\rm ext}}[(1-\kappa_1)(1-\kappa_2)e^{-j\beta L_1}] \end{aligned} \tag{4}$$

$$P_2 = (1)(4)(8)(9)(11) = \kappa_1\kappa_2 e^{-j\beta L_{\rm ext}} e^{-j\beta L_2} \tag{5}$$

$$L_1 = (3)(7)(10)(2)(3) = \kappa_1\kappa_2 e^{-j\beta L_1} e^{-j\beta L_0} \tag{6}$$

$$\begin{aligned} L_2 &= (4)(8)(10)(2)(4) = (1-\kappa_1)(1-\kappa_2)e^{-j\beta L_0} \\ &\quad \cdot e^{-j\beta L_2}. \end{aligned} \tag{7}$$

Reporting (4)–(7) into the Mason's rule (3), we easily get the equation shown at the bottom of the page, where $\chi = (1-\kappa_1)(1-\kappa_2)$ and$\xi = \kappa_1\kappa_2$.

The transfer function $H(\omega_{\rm RF})$ [(8), shown at the bottom of the page] allows us to simulate the microwave frequency response of the optical network. For an ideal 3-dB optical coupler and a given set of parameters $L_{\rm ext} = 1$ m, $\Delta L = 40$ cm, $L_0 = 2$ m, the simulated results in the modulating frequency range (0–2 GHz) are given Fig. 4.

$$H(\omega_{\rm RF}) = \frac{I_{11}}{I_1} = e^{-j\beta L_{\rm ext}} \frac{\chi \exp(-j\beta L_1)\{1-\chi\exp[-j\beta(L_0+L_2)]\} + \xi\exp(-j\beta L_2)\{1-\xi\exp[-j\beta(L_0+L_1)]\}}{1-\chi\exp[-j\beta(L_0+L_2)] - \xi\exp[-j\beta(L_0+L_1)]} \tag{8}$$

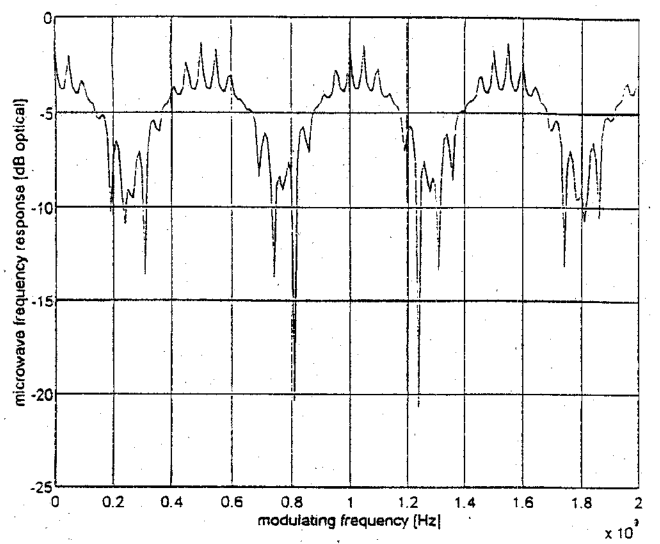


Fig. 4. The simulated microwave frequency response (dB optical) of the Recirculating Unbalanced Mach-Zehnder in the modulating frequency range (0–2 GHz).

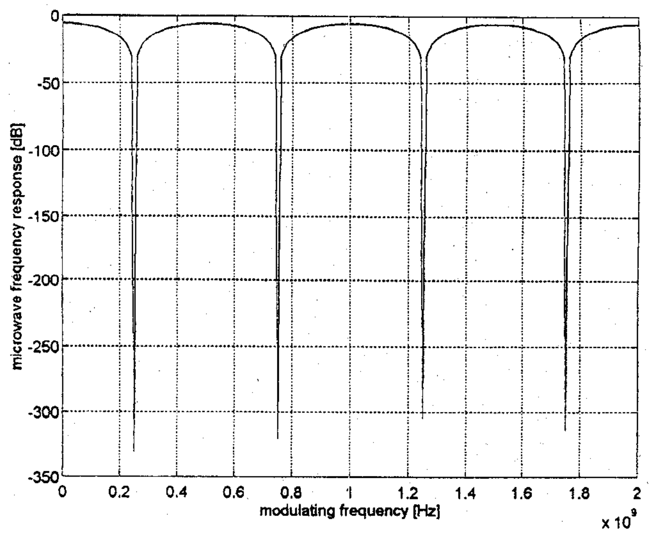


Fig. 5. The simulated microwave frequency response (dB optical) of the Unbalanced Mach-Zehnder interferometer in the modulating frequency range (0–2 GHz).

B. The Unbalanced Mach-Zehnder and the Fabry-Perot Ring Resonator

The Unbalanced Mach-Zehnder (UMZ) and the Fabry-Perot Ring Resonator (FPRR) are two structures usually used in fiber-optic microwave signal processing applications [4], [6]. The graphical representation of the FPRR is given Fig. 3 and that of the UMZ can be easily obtain from the graph Fig. 2 by disconnecting the two nodes (2) and (10). Applying the same technique described above, we get the microwave frequency responses of these structures: For the UMZ

$$\frac{I_{11}}{I_1} = H(\omega_{\rm RF}) = \exp(-j\beta L_{\rm ext})\{(1-\kappa_1)(1-\kappa_2) \cdot \exp[-j\beta(L_1 - L_2)] + \kappa_1\kappa_2\} \tag{9}$$

and for the FPRR

$$\frac{I_5}{I_1} = H(\omega_{\rm RF}) = \exp(-j\beta L_{\rm ext}) \cdot \frac{\kappa + (1-2\kappa)\exp(-j\beta L)}{1 - \kappa\exp(-j\beta L)}. \tag{10}$$

Thus the simulated results of the microwave frequency response for these structures are also given Figs. 5 and 6(a) and (b), respectively. The simulated phase response of the FPRR is given Fig. 6(b) in order to compare with the measurement result [Fig. 9(b)].

III. Experimental Setup

The schematic diagram of the setup used in the experiment is shown in Fig. 7, where the HP 8510 vector network analyzer is used for the generation of the microwave modulating signal as well as its detection. A directly modulated DFB laser diode butt-coupled to a single-mode fiber without an optical isolator was used as the light source in our measurements. The reflected light on the laser diode caused it to be multimode and then destroyed its coherence property. For the detection, a lightwave test set with a high-speed detector and a microwave preamplifier is used. The detection bandwidth of the photodetector and the RF amplifier is 20 GHz, however the measurements are performed only up to 3 GHz due to the bandwidth limitation of the modulated laser diode. The effects of the variations in the frequency response of the laser diode and the photodetector are eliminated by making a direct thru connection and using it for the calibration.

For the optical network construction we have used 3-dB optical couplers, different lengths of optical fibers, and FC/PC optical connectors. All the optical elements are single mode at the operating wavelength of 1.3 μm. In each case we assembled some previous elements to obtain the required optical network. The following optical network configurations are tested:

1) The Unbalanced Mach-Zehnder interferometer (UMZ) where two 3-dB couplers are used as optical Y-junctions and two fibers of different lengths L_1 and L_2 are used as the interferometer arms. The characteristic parameter of this network is the length difference between the two arms $L = L_2 - L_1 = 40$ cm.
2) The Fabry-Perot Ring Resonator (FPRR, Fig. 3) that uses one 3-dB coupler and a fiber of length L as a loop between two ports of the optical coupler. The characteristic parameter of the FPRR is the length L of the loop. In our experiment $L = 2$ m. This element simulates the Fabry-Perot interferometer usually used in optics.
3) The Recirculating Unbalanced Mach-Zehnder (RUMZ, Fig. 2.). This network has two characteristic lengths, one corresponds to the UMZ, $\rm L_{UMZ} = 40$ cm and the other corresponds the length of the RR, $\rm L_{RR} = 2$ m.

In the previous networks, all the elements are single-mode optical fibers and the two couplers have roughly the same characteristics.

IV. Experimental Results

For the optical fiber UMZ the difference length between the two arms was 40 cm. The measured microwave transfer

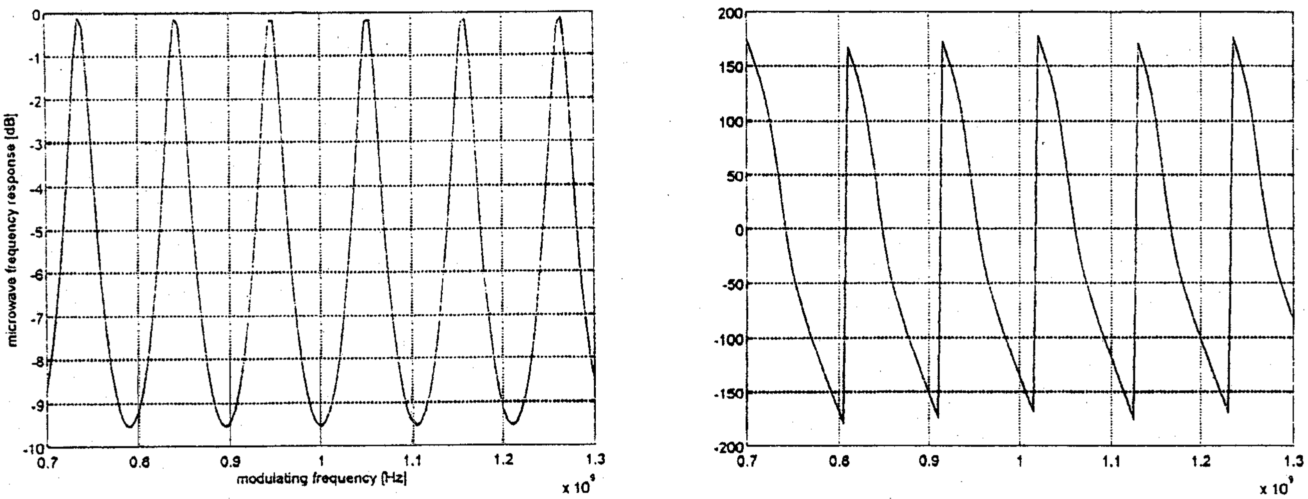


Fig. 6. The simulated microwave frequency response of the FPRR in the modulating frequency range (0.7–1.3 GHz). (a) Magnitude (in dB optical) and (b) phase (in degree).

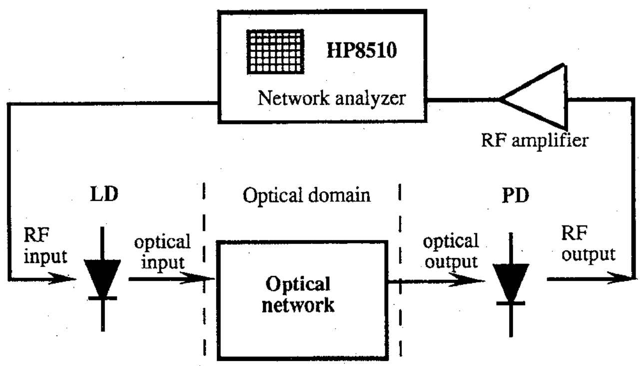


Fig. 7. Experimental setup based on the use of a microwave vectorial network analyzer. The modulated laser diode and the high-speed photodetector are used as wideband E/O and O/E converters.

function (magnitude and phase) is given on Fig. 8. One notices that this response corresponds to a notch filter. The measured rejection ratio is better than 35 dB for the rejected frequencies and may approach 50 dB for certain frequencies. The first rejected frequency is around 252 MHz and the distance between two rejected frequencies is 505 MHz. As far as the phase response is considered, it shows a very good linearity. The stability of the difference between rejected frequencies as well as the phase linearity of the device are due to the very low dispersion of the optical waveguide, i.e. the optical fiber. Comparing these results to the simulated ones (Fig. 5) we can notice a very good agreement.

Now we consider the second network, the Fabry-Perot Ring Resonator with $L = 2$ m. The measured transfer function is given Fig. 9. The response corresponds to a ripple of the amplitude with a depth around 9 dB and a frequency of modulation of 105 MHz. The modulation depth depends only on the coupling coefficient of the optical coupler and is twice of this coefficient because 1 dB in optical domain is equivalent to 2 dB in electrical domain. The frequency modulation seen in this response depends on the length of the loop, which is 2 m and corresponds to a frequency of 105 MHz. If we compare

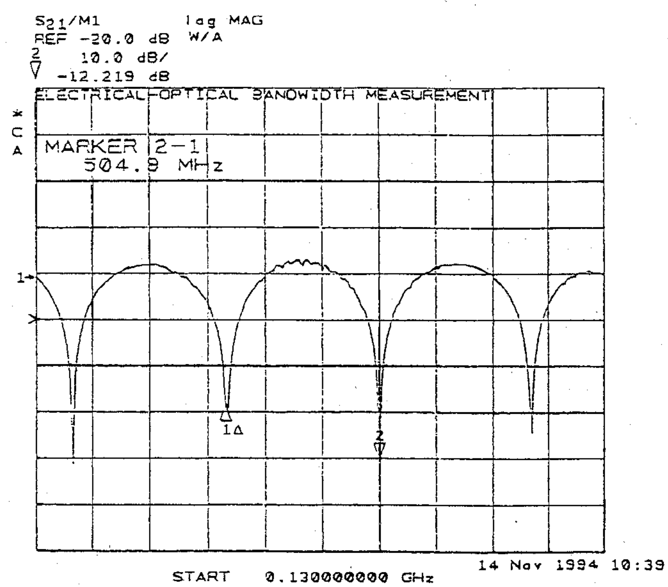
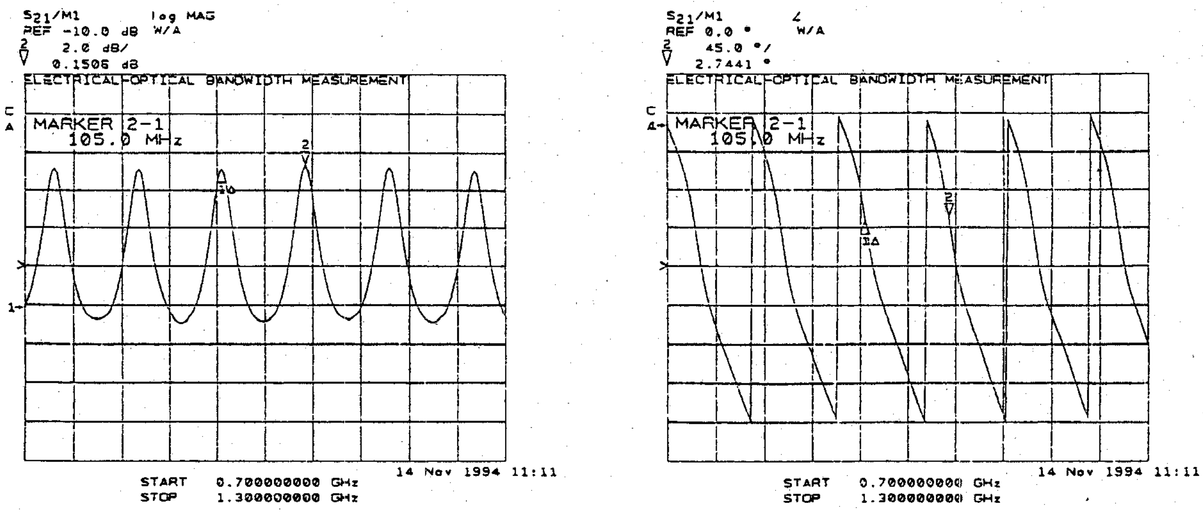


Fig. 8. Measured transmission coefficient of the optical fiber UMZ (dB electrical). This device can be used as a microwave rejection filter.

this measured magnitude to the simulated one [Fig. 6(a)], we obtain a difference of 5 MHz on the modulation frequency. This is due to the difficulty to obtain in practice exactly 2 m for the ring resonator. The measured phase is given Fig. 9(b). As predicted by the simulation [Fig. 6(b)] the phase response is not linear at all and we have different regions with high or low variations of the phase.

The third measured optical network is the RUMZ, which can be considered as a combination of the UMZ and the FPRR (Fig. 2). The two characteristic lengths of this network are $L_{\text{UMZ}} = 40$ cm and $L_{\text{RR}} = 2$ m, corresponding exactly to the two previous networks. The measured transfer function is given Fig. 10, which also agrees well with the corresponding theoretical results presented above (Fig. 4). We obtain a rejecting filter in which the rejected frequencies depend on L_{UMZ} modulated by the response of the FPRR where the modulation



(a) (b)

Fig. 9. Measured transmission coefficient of the optical fiber FPRR as a function of the modulating frequency. (a) Magnitude. (b) Phase.

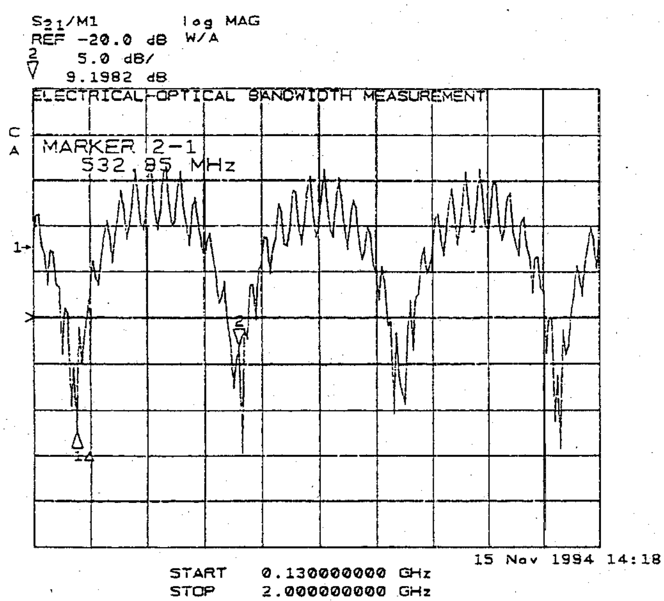


Fig. 10. Measured transmission coefficient of the optical fiber RUMZ (dB electrical) as a function of the modulating frequency.

depth and frequency depends on the coupling coefficient and the L_{RR}, respectively.

V. CONLUSION

In this paper we considered the optical networks in order to perform microwave functions. We studied and realized several all-optical networks that can be used as microwave devices. The analysis of these devices uses the S-matrices and the graph techniques well-known in electrical circuit analysis. The microwave frequency response of optical networks depends on their geometrical topology and the lengths of the optical paths. As a matter of fact, for the Unbalanced Mach-Zehnder it is evident that the rejected frequencies can be easily controlled if we change the path difference [6]. This gives a large domain of application as the length difference can easily be varied from some centimeters to some ten's of meters. Moreover, the same concept can be used in the case of millimeter-waves where an integrated optical device with a path difference less than 1 cm can be easily fabricated. An integrated UMZ on glass substrate where the path difference was 6.6 mm and the first rejected frequency around 15 GHz has been demonstrated [7]. The same integration can be conducted for the other optical networks in order to reach the millimeterwave ranges.

Finally, the same optical network can also be used to perform "active" microwave functions. This can be done if we use electrooptic substrates like $LiNbO_3$, which allows the realization of tunable microwave devices. On the other hand, modulating the laser diode results in an optical frequency modulation that can be transformed into intensity modulation by the unbalanced interferometer. This enables to use this configuration for the generation of microwave signals. Interesting results concerning this application have already been obtained using a volume unbalanced interferometer [9]. However, in this case, the laser diode coherence is an important parameter.

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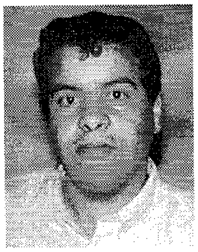

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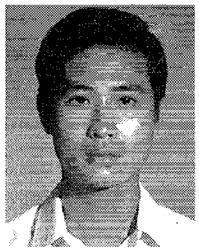

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