Experimental Investigation on the Optical Unbalanced Mach–Zehnder Interferometers as Microwave Filters

Anh Ho Quoc and Smaïl Tedjini, *Senior Member, IEEE*

Abstract— **In this work, we study the propagation effects of a modulated lightwave signal in an unbalanced Mach-Zehnder interferometer (UMZI). Experimental results of the microwave frequency response of the structure are obtained using two lightwave network analyzers HP8702A and HP8510B with an optoelectronic HP83420A. It is shown that such an optical device could be used to perform a number of interesting microwave applications. The problems appearing in the coherent working regime and the possibility of integrated device realizations for millimeter-frequency signal processing are also discussed.**

I. Introduction

In RECENT YEARS, applications of optical waveguide devices in communication and sensing systems have become familiarized. On the other hand, optical structures performing a wide variety of operations in the microwave signal processing applications such as filtering, convolution, and correlation, have been proposed [1]. The two basic optical structures usually used for signal processing applications are the recirculating delay lines and the nonrecirculating delay lines [2]. The **UMZI** can be classified as the last kind. When an amplitude modulated light at microwave frequencies is fed into such a structure, due to the interference effects of the modulated optical signals delayed on the two different path lengths, the output optical intensity will depend not only on the amplitude modulation but also on the microwave modulating frequency. Therefore, a microwave frequency response (**MFR**) of the whole structure can be defined as a relation between the input electrical modulating signal and the detected electrical output signal.

In fact, when two or more modulated lightwave signals propagating on different optical paths are recombined at the output of the structure, one can regard the effect as the consequence of two interference phenomena. The first one is due to the optical carrier (at optical frequencies) and the second is due to the microwave envelope signals (at microwave frequencies). The interference effect of the microwave envelope leads to the resonances in the **MFR**, while that of the optical carrier could affect its characteristics.

In this letter, we consider the microwave characteristics of an **UMZI** when excited by incoherent and coherent modulated lightwave signals.

Manuscript received January 31, 1994.
The authors are with the Laboratoire d'Electromagnétisme, Micro-Ondes et Optoélectronique, LEMO, Grenoble, France.
IEEE Log Number 94021275.

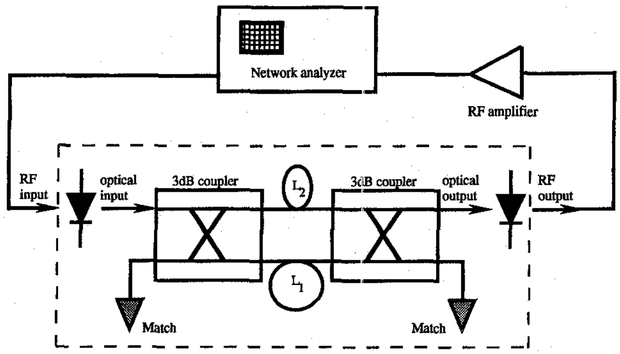

Fig. 1. Unbalanced Mach–Zehnder interferometer as a "microwave device."

II. Experiments and Results

The **UMZI** is realized using connectorized elements: two single-mode fibers of different lengths (L_1 and L_2), two -3-dB fiber directional couplers as shown in Fig. 1. The optical connectors used are the FC-PC standard, which present low losses (< 0.5 dB per connection) and a high repeatability. In our first experiment, the input of the optical structure is excited by an amplitude modulated optical signal transmitted by a Fabry–Perot laser diode working at the wavelength 1.3 μm. The fiber length difference used was much longer than the coherence length of the laser diode (144–20 cm). Thus, an incoherent working regime of the structure may be assumed. The output of the optical device under test is followed by a high-speed PIN photodetector for extracting the microwave signal. The electrical detected signal will be compared with the modulating one in both amplitudes and phases. Consequently, the **MFR** of the device can be displayed by a lightwave test set HP8702A. For accurate measurement results, a preliminary stage of through connection calibration and an ensemble average of coefficient 64 are required.

One can regard the whole system (laser source, optical structure, and detector) as a "microwave device." Optoelectronic scattering parameters were used for black box characterization of the device as proposed in [3]. Let S_{21}^{op} be the optoelectronic transmission scattering parameter displayed by the lighwave test set, the electrical scattering parameter $S_{21}^{e} = 2S_{21}^{op}$ of the microwave device defined above is related by $S_{21}^{e} = 2S_{21}^{op}$.

Fig. 2 shows periodic variations in amplitude of S_{21}^{op} displayed in the range 0.3–500 MHz. Such a response corresponds to that of a microwave notch filter. The maximum

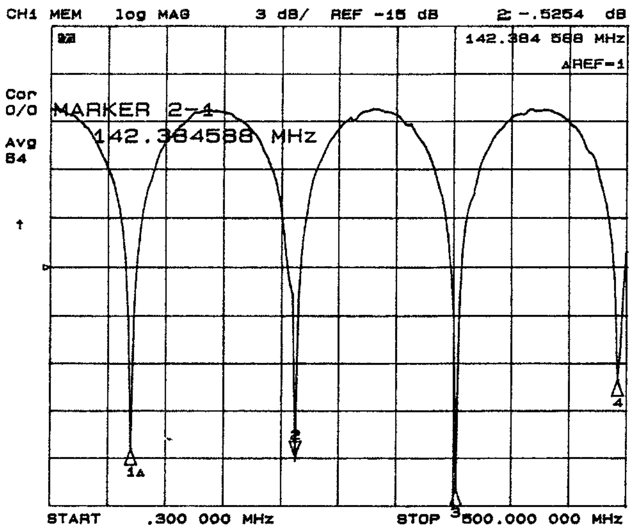

Fig. 2. Amplitude varition of S_{21}^{op} (in dB) as a function of the modulating frequency. The optical path length difference is 144 cm. The coherence length of the light source is 20 cm, vertical scale: 3 dB/div, reference value: -15 dB.

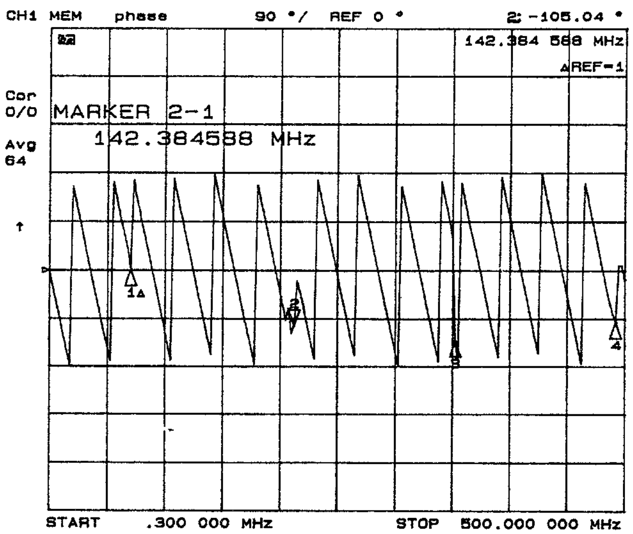

Fig. 3. Phase varition of S_{21}^{op} (in degree) as a function of the modulating frequency.

rejection ratio S_{21}^{e} exceeding 40 dB is readily obtained at resonant frequencies that may be easily determined as follows:

$$f_{res} = (2k+1)\frac{c}{2N(L_2 - L_1)}$$

where N is the effective index of the single-mode fibers (1,46 in our experiment); c is the speed of light in the free space, and $k = 0, 1, 2, \cdots$

Corresponding to an optical path difference of $L_1 - L_2 =$ 144 cm, a first resonant frequency at 71.1 MHz (corresponding to k=0) and a distance of 142.3 MHz between resonant frequencies are observed. A good linearity in the phase variation of S_{21}^{op} is also obtained like that of a microwave transmission line (see Fig. 3). For microwave applications, such a good linear phase variation is usually desired.

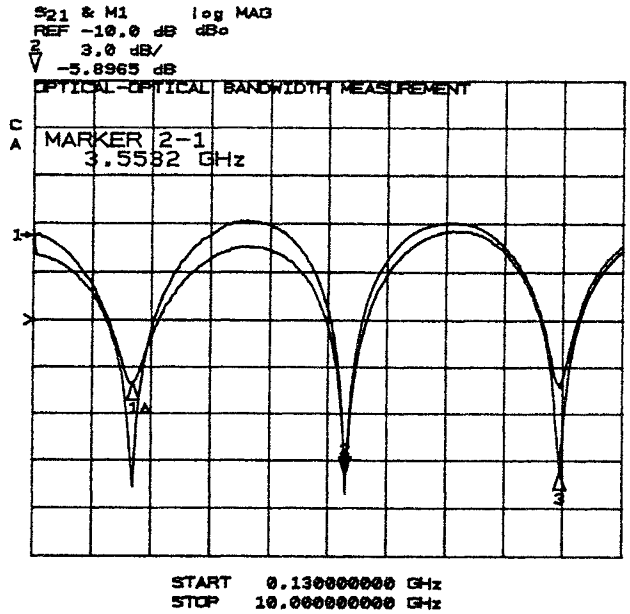

Fig. 4. Amplitude varition of S_{21}^{op} (in dB) as a function of the modulating frequency at different measurement times. The optical path length difference is 3 cm. The coherence length of the light source: 6 m, vertical scale: 3dB/div, reference value: -10 dB.

In order to investigate the optical interference effects in the coherent working regime, we have realized an **UMZI** with a short optical path difference $L_1 - L_2 = 3$ cm. The input of the structure is now excited by a modulated optical signal with a coherence length of 6m transmitted by a DFB laser diode. The amplitude modulation is made externally by a broadband electrooptical modulator. Using a network analyzer HP8510B with an optoelectronic HP83420A, the frequency response of the structure is measured in the modulating frequency range 130MHz–10GHz as shown in Fig. 4.

A first resonant frequency at about 1.77 GHz and a distance of 3.55 GHz between resonant frequencies are observed. An optical rejection ratio of S_{21}^{op} exceeding 18 dB is also obtained, corresponding to an electrical rejection ratio 36 dB. However, because the coherence length of the optical carrier is much longer the optical path difference (6 m to 3 cm), in this experiment the effects of the optical interference have become evident. Variations in the rejection depths and in the behavior of the frequency response were observed at different measurement times. This is due to the unstability of the relative optical phase shift between the two interferometer's arms, which is very sensitive with the ambient variations and the optical chirp. This phenomenon can be interpreted by a theoretical analysis of the optical structure in the case of coherent working regime. We have observed that when the variation of the optical path difference is in the order of a fraction of the optical wavelength, the microwave characteristics of the structure can be strongly influenced.

III. Discussion and Conclusion

The experimental results of the frequency response of a fiber-based **UMZI** show that these devices can act as microwave notch filters. For high-frequency filtering applications, much shorter optical path length difference will be needed. Such a short length difference can be easily achieved using integrated devices.

Considering the overall system (modulated light source, optical circuit, detector), the RF-to-optical and the optical-to-RF conversions losses must be taken into account in the whole frequency response. These losses are generally in the order of 20–50 dB for direct modulation and 30–60 dB for external modulation. Thus, a RF amplifier is required to compensate the losses as usually used in any fiber-optic link. Nevertheless, when using an external modulation scheme, it has been demonstrated [4] that a net RF gain can be obtained without amplification for optical power sufficiently high (in the order of 10 mW).

The **MFR** of the structure is determined by the tap coefficients of the two optical paths and the relative delay time between them. In the incoherent working regime, these tap coefficients must be positive real values. This limits the possibility for realizing certain transfer function forms. Conversely, in the coherent regime, the optical polarization states and the relative optical phase shift must be strictly controlled for maintaining a stable functioning. However, the characteristics of the **MFR** could be tunable by varying these optical phase shifts [5]. Using the coherent regime, one can arbitrarily choose the complex's tap coefficients and synthesize **MFR**'s that cannot be realized when using the incoherent regime.

REFERENCES

[1] B. Moleshi, J. W. Goodman *et al.*, "Fiber-optic lattice signal processing," *Proc. IEEE.* vol. 72, no. 7, July 1984.

[2] K. P. Jackson, S. A. Newton *et al.*, "Optical fiber delay-line signal processing," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-33, no. 3, Mar. 1985.

[3] D. D. Curtis and E. E. Ames, "Optical test set for microwave fiber-optic network analysis " *IEEE Trans. Microwave Theory Tech.,* vol. 38, no.5, May 1990.

[4] C. H. Cox III, G. E. Betts *et al.*,"An analytic and experimental comparison of direct and external modulation in analog fiber-optic links," *IEEE Trans. Microwave Theory Tech.,* vol. 38, no. 5, May 1990.

[5] Chin-Lin Chen,"Optical fiber Fabry-Perot cavities and recirculating delay lines as tunable microwave filters," *IEEE Trans. Microwave Theory Tech.,* vol. 38, no. 5, May 1990.