Theoretical & Experimental Study of Single Mode Fiber Optical Ring Resonators for Microwave Applications

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Abstract - **The propagation effects of a microwave intensity modulated light in a fiber based optical ring resonator are studied. Experimental and theoretical investigations on the microwave behavior of the device show the possibility of its use as a microwave filter. Significant changes on the microwave behavior are observed when using a coherent light source due to optical interferences of the light carrier. The concept of optical scattering parameters is applied in order to model the microwave behavior of the device.**

I. INTRODUCTION

Single mode optical fibers are nowadays well known as an excellent waveguide medium with very low losses and large length-bandwidth product. These properties are attractive for true time delay applications. The use of optical fiber delay lines to perform a wide variety of signal processing functions such as filtering, pulse train generation and matrix operations at radio frequencies was proposed and demonstrated by several authors during the last decade [1]-[2]. The main advantages of this technique are the possibility of very wide band signal processing and the operations are performed directly in the optical domain.

The fiber-based ring resonator is a well known optical device which has several important applications in optics. In this paper, we study the microwave behavior of the device and show the possibility of its use as a microwave filter. Most of the previous works have been done in the incoherent working regime of the device, i.e. when the length of the optical delay line used in the device are much longer than the coherence length of the light source. However, in microwave signal processing, the delay line length needed is usually small in comparison with the coherence length of the light source, especially when high quality optical sources are used like DFB lasers. The interference effect of the light carrier plays an important role in the microwave behavior of the device and must be considered properly.

II. THEORY

The theoretical analysis of the fiber-based optical ring resonator excited by a modulated quasi-coherent light was reported in the literature [3]. The author used a time domain analysis which is able to express the effects of the coherence length of the light source on the Microwave Frequency Response (MFR) of the structure in an explicit form. This method requires a quite complex series summation to evaluate the output optical field. When using a laser under direct modulation, such a method cannot conveniently be applied because of its complexity. We modeled the structure by a simpler method, which involves the use of the optical scattering parameters [5] and a graphical representation technique [6] to calculate the output optical field and the MFR of the structure in the frequency domain.

The optical scattering matrix [S] is defined as a linear relation between the incident and the reflected optical fields in a multiport optical component :

$$[b_i] = [S_{ij}][a_j] \qquad (1)$$

In general, b_i and a_j must be Jones vectors to be able to describe the polarization states of the optical field. Provided the guiding structure is single mode and polarization degenerated, they become simply scalar complex quantities.

The studied ring resonator is shown Fig. 1.a. It includes a single mode optical coupler and a feedback single mode optical fiber of length L. In the case of polarization preserving optical couplers, the scattering matrix for each polarization state has the following general form [5] :

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$$[S]=\begin{bmatrix} 0 & 0 & e^{j\phi}\cos\theta & e^{j(\pi-\psi)}\sin\theta \\ 0 & 0 & e^{j\psi}\sin\theta & e^{-j\phi}\cos\theta \\ e^{j\phi}\cos\theta & e^{j\psi}\sin\theta & 0 & 0 \\ e^{j(\pi-\psi)}\sin\theta & e^{-j\phi}\cos\theta & 0 & 0 \end{bmatrix} \quad (2)$$

where θ, ψ, ϕ are the parameters which characterize the optical coupler.

The graphical representation of the optical structure is given Fig.1.b. Using the well known graph reduction rules, we obtained the optical field transfer function of the device:

$$T(\nu) = -e^{2\pi j\nu\tau}\,\frac{1-e^{-j(2\pi\nu\tau+\phi)}\cos\theta}{1-e^{j(2\pi\nu\tau+\phi)}\cos\theta} \quad (3)$$

where ν is the optical frequency, $\tau = LN/c$ is the optical delay time introduced by the fiber loop length and N is the optical effective index of the fiber. For a given spectral distribution of the intensity modulated light source and assuming an ideal phototedector at the output of the optical structure, the photocurrent can be easily calculated by:

$$I_{ph} \approx \left\langle E_{out}(t)\,.\,E^{*}_{out}(t)\right\rangle \quad (4)$$

Taking the first microwave harmonic of the photocurrent obtained in (4) by using a Fast Fourier Transform procedure, we are able to simulate numerically the MFR of the device.

Moreover, in the case of a non coherent light source, an analytical expression of the MFR can be obtained. Instead of using (2), the intensity input-output relationship of a symmetric, matched optical coupler can be used :

$$\begin{bmatrix} I_5 \\ I_6 \end{bmatrix} = \gamma \begin{bmatrix} 1-\kappa & \kappa \\ \kappa & 1-\kappa \end{bmatrix} \begin{bmatrix} I_3 \\ I_4 \end{bmatrix} \quad (5)$$

Where κ is the is the intensity coupling cefficient and γ characterizes the total optical losses in the coupler. The feedback fiber L used in the structure introduces only a microwave phase shift to the modulated signal:

$$I_1 = I_7\, e^{-j\beta L} \quad (6)$$

where $\beta = \omega_{RF} n_{eff}/c$; n_{eff} is the effective index of refraction and c the speed of light. Thus, the microwave transfer function of the ring resonator is:

$$H(\omega_{RF}) = \exp(-j\beta L_{ext})\,\frac{\kappa + (1-2\kappa)\exp(-j\beta L)}{1-\kappa\exp(-j\beta L)} \quad (7)$$

Where L is the length of the feedback fiber and L_{ext} is a fiber length to take into account of the connection fibers at the input and the output of the ring resonator.

Simulated results of the MFR for a fiber loop length of 20 cm and a -3dB optical coupler in the modulating frequency range 1MHz-3GHz is given in Fig.2.a,b. This case corresponds to a quasi-coherent working regime of the structure because the coherence length of the light source used in our simulation is 4m. We observed that a very small change in the fiber loop length (in the order of tenth optical wave length) can make a significant change on the MFR of the device.

III. EXPERIMENTAL INVESTIGATIONS

The single mode fiber ring resonator was realized using connectorized elements: a -3dB fiber directional coupler and a fiber loop length L as shown in Fig.1.a. The input of the optical structure is excited by an amplitude modulated optical signal generated by a DFB laser diode operating at the wavelength 1.3 µm and an external modulator. The coherence length of the laser source is about 4m in the fiber medium, corresponding to a spectral linewidth of 50MHz. The output of the optical device under test is followed by a high speed PIN photodetector for the extraction of the microwave signal. The electrical detected signal is compared with the modulating one in both amplitude and phase. When sweeping the modulating frequency, the MFR of the device can hence be displayed using a vectorial network analyzer.

In order to study the MFR of the device in both the incoherent and the coherent working regimes, we used different fiber loop lengths. First, the fiber loop length used was much longer than the coherence length of the laser diode (24 m to 4 m). Thus, an incoherent working regime of the structure can be assumed. The measured MFR of the device (in amplitude and phase) is given Fig.3, displayed in the modulating frequency range 1GHz - 1.05GHz. A periodic variation of 4dB optical (i.e. 8dB electrical) was obtained showing multiple resonant frequencies. The oscillation depth depends on the coupling coefficient of the optical coupler and the periodicity of the response depends on the length of the fiber loop. The obtained response is quite stable because the effects of the optical interferences are negligible in this case. These experimental results are in good agreement with the predicted theoretical results obtained by Eq.7 (not presented here).

Fig.4.a. shows the MFR of the device when the fiber loop length was reduced to be about 2m, which is smaller than the coherence length of the light. Significant variations can be observed (>10dB optical) in the range 130MHz-1GHz. As predicted in theory (Fig.2), such a response corresponds to that of an electric notch filter. The changes observed in the microwave behavior of the device are due to the interference effects of the light carrier, which is very sensitive to the optical phase changes, the laser chirp and the polarization states of the light. If these optical parameters are not controlled precisely, the MFR of the device can be quite unstable as shown in Fig 4b.

IV. CONCLUSION

The microwave behavior of fiber-based optical ring resonator is studied. We demonstrated the possibility of their use as microwave filters. When working in the coherent regime, the MFR of the structure can be made tunable by introducing a controlled small change in the optical path length. The theoretical analysis was performed by a simple method and it can be applied conveniently for complex optical signal processing structures. This method can be easily extended to involve the effects of the optical polarization and the frequency-amplitude intermodulation of the light source.

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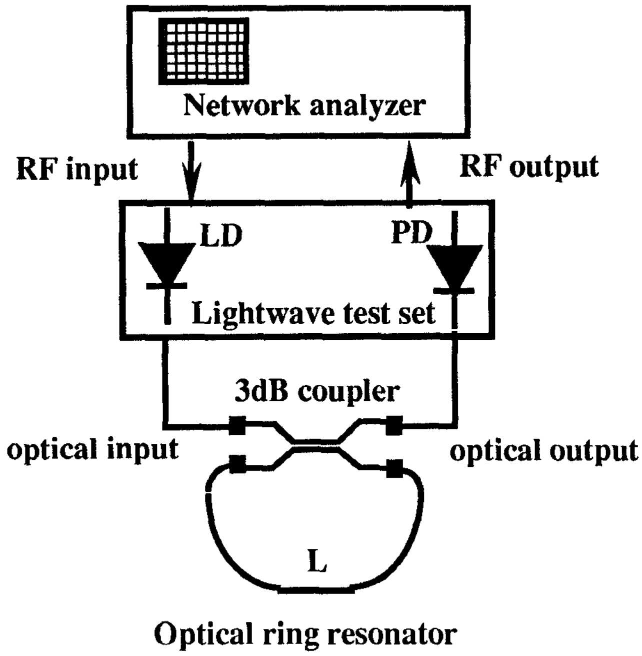


Fig. 1. a. *Experimental configuration*

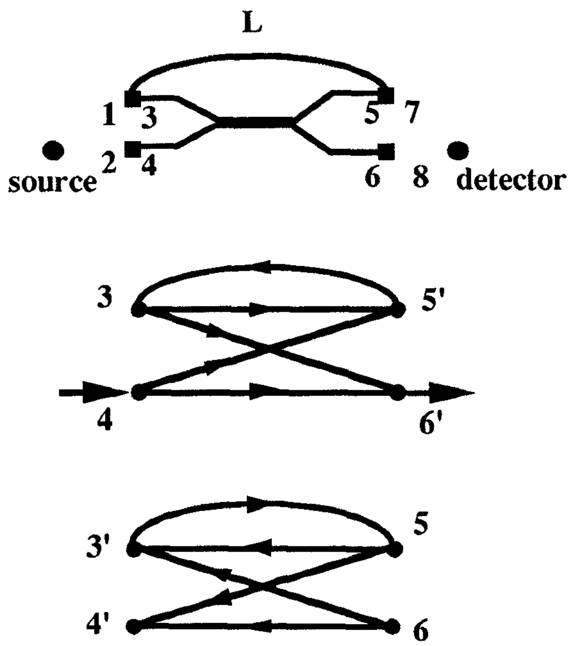


Fig. 1.b. *Graphical representation of the optical structure.*

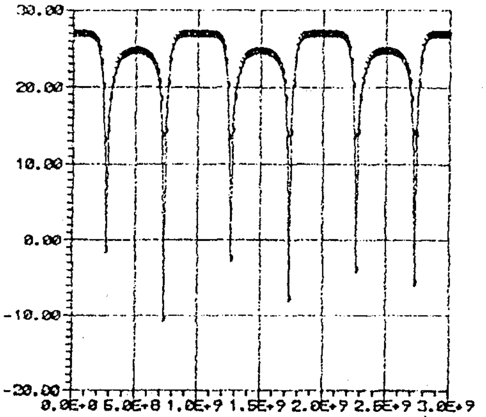


Fig.2 a)*Simulated results of the MFR of the structure.*(in dB relative)

For L=150000 λ_{opt} =19.5 cm

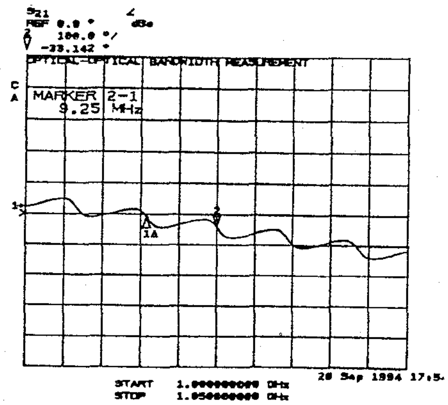


Fig.3 b) *Measured phase of the MFR in the incoherent working regime for* L=24m

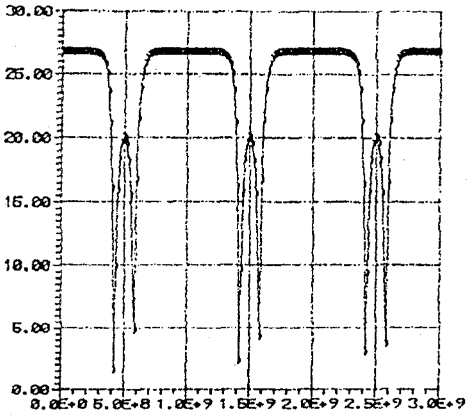
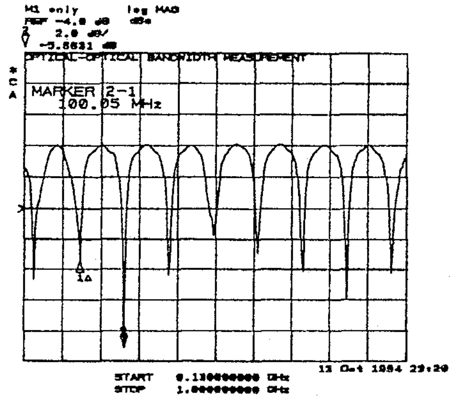


Fig.2 b)*Simulated results of the MFR of the structure.*(in dB relative)

For L=150000 λ_{opt} +0.1λ_{opt}



a).

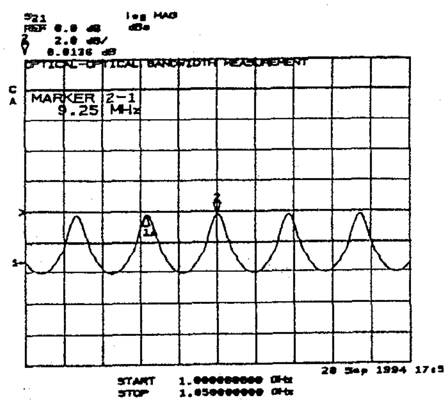
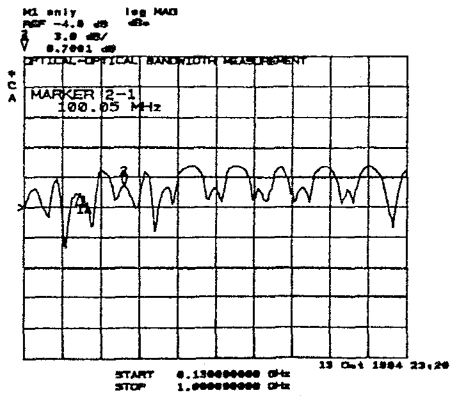


Fig.3 a)*Measured magnitude of the MFR in the incoherent working regime for* L=24m



b).

Fig.4.a,b *Measured results of the MFR for* L=2m. *This case corresponds to a quasi-coherent working regime.*