Independent Group Delay and Amplitude Manipulation Based on a Micro-Ring Resonator for Optical Microwave Beam-Steering

Z. Cao, Y. Jiao, H.P.A. van den Boom, E. Tangdiongga, and A.M.J. Koonen

COBRA Institute, Eindhoven University of Technology, NL 5600 MB Eindhoven, The Netherlands
z.cao@tue.nl

***Abstract**: Optical microwave beam-steering is of interest for broadband wireless communication and phased array radar. Traditionally the optical all-pass filter (OAPF) based on a micro-ring resonator (MRR) can only be used to manipulate group delay. Moreover, the requirement of lossless condition of the OAPF limits its potential of monolithic integration on an InP platform. To overcome this limitation and also to provide freedom for amplitude manipulation, a novel loss-control MRR is proposed for both group delay and amplitude manipulation. A mathematical model has been developed for analysis and simulations are carried out to study the proposed design.*

I Introduction

Optical microwave beam-steering (OMBS) is of interest for broadband phase antenna arrays due to its wide bandwidth, low loss and immunity to electromagnetic interference. In previous research, most efforts are made for military application like broadband phase array radar. Recently, the utilization of OMBS for broadband fibre wireless communication attracts lots of interest. The key enabling technique is the suitable optical delay unit (ODU). The micro-ring resonator (MRR) based ODU are gaining high interest in terms of integration capability, design flexibility and small footprint [1-3]. MRRs require no cleaved facets or grating couplers to realize optical feedback and are therefore particularly suited for monolithic integration with other components. These applications of MRRs are based on the concept of the optical all-pass filter (OAPF). Traditionally the OAPF based on a micro-ring resonator (MRR) can only be used to manipulate the group delay. Moreover, the requirement of lossless condition of the OAPF limits its potential of monolithic integration on an Indium-Phosphide (InP) platform. To overcome this limitation and also to provide freedom for amplitude manipulation, a novel loss-control MRR is proposed for both group delay and amplitude manipulation. A mathematical model has been developed for analysis and simulations are carried out to study the proposed design.

II. Theoretical Model, Analysis and Simulation

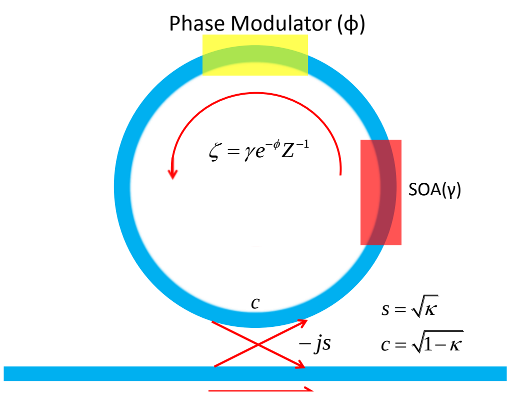

Fig. 1. The principal scheme of lattice double chain

The structure of the OAPF based on an MRR is depicted in Fig.1. A straight waveguide is coupled to the micro-ring. The coupling ratio of the directional coupler formed by the straight waveguide and part of the ring can be controlled by adjusting the gap and the coupling length between the straight waveguide and the ring. The phase shift can be realized by tuning the refractive index of the ring waveguide by thermal-optic or electro-optic methods. The loss inside the MRR can be adjusted by the in-ring semiconductor optical amplifier (SOA). In previous publications, the loss in the ring is usually neglected for a lossless platform like SiN. In this case all input optical power will eventually arrive at the output port. This structure is so called optical all-pass filter because of this constant amplitude of the transfer function. The loss cannot be neglected for platforms like InP. It is therefore important to understand the role of the losses. In the following sections, the impact of loss will be modelled and analyzed for the transmission function and the group delay function.

A. General modelling of an OAPF with loss

The transfer function of an OAPF can be modelled based on Z-Transform. In the Z-domain, the input and output optical signal can be expressed as *X* and *Y*, respectively. As shown in Fig.1, the through and cross transmissions between the straight waveguide and ring are noted as *c* and *s*. The delay, phase shift and loss inside the ring is modelled as ζ as shown in Fig.1. Thus the relationship between input and output can be expressed as:

$$Y = cX + X(-js)\zeta(-js) + X(Z^{-1})(-js)\zeta c\zeta(-js) + X(-js)\zeta c\zeta c\zeta(-js) + ... \tag{1}$$

This can be simplified as: $Y = X(c-\zeta)/(1-c\zeta)$. Thus the transfer function *H* can be expressed as:

$$H = Y/X = -\gamma e^{-j\phi}(-c\gamma^{-1}e^{j\phi} + Z^{-1})/(1-c\gamma e^{-j\phi}Z^{-1}) \tag{2}$$

In the following, the impact of loss to the square magnitude response and the group delay response will be discussed based on Eq.2.

B. Square magnitude response of an OAPF with loss

The power transfer is useful for optical system design and easy to measure. Thus the square magnitude response is important for optical filter design. The square magnitude response can be expressed as:

$$\begin{aligned}
\left|H(e^{j\Omega T})\right|^2 &= \left|-\gamma e^{-j\phi}(-c\gamma^{-1}e^{-j\phi} + e^{-j\Omega T})/(1-c\gamma e^{-j\phi}e^{-j\Omega T})\right|^2 \\
&= \gamma^2\left|(-c\gamma^{-1}e^{+j\phi} + e^{-j\Omega T})\right|^2 / \left|1-c\gamma e^{-j\phi}e^{-j\Omega T}\right|^2 \\
&= \frac{\gamma^2[-c\gamma^{-1}\cos(\phi)+\cos(\Omega T)]^2 + \gamma^2[c\gamma^{-1}\sin(\phi)+\sin(\Omega T)]^2}{[1-c\gamma\cos(\phi+\Omega T)]^2 + c^2\gamma^2\sin^2(\phi+\Omega T)} \\
&= \frac{c^2+\gamma^2-2c\gamma\cos(\phi+\Omega T)}{-2c\gamma\cos(\phi+\Omega T)+1+c^2\gamma^2}
\end{aligned} \tag{3}$$

where Ω and T are normalized angular frequency and round trip time of the ring. Next we investigate the impact of loss. If the loss is neglected, the value of γ is equal to 1, and the square magnitude response can be expressed as:

$$\left|H(e^{j\Omega T})\right|^2 = \frac{c^2+1-2c\cos(\phi+\Omega T)}{-2c\cos(\phi+\Omega T)+1+c^2} = 1 \tag{4}$$

If the loss is too large to be neglected, the square magnitude response can be expressed as:

$$\left|H(e^{j\Omega T})\right|^2 = \frac{c^2+\gamma^2-2c\gamma\cos(\phi+\Omega T)}{-2c\gamma\cos(\phi+\Omega T)+1+c^2\gamma^2} = 1+\frac{(\gamma^2-1)(1-c^2)}{1+c^2\gamma^2-2c\gamma\cos(\phi+\Omega T)} \tag{5}$$

According to Eq.5, the square magnitude response should be bell-shaped curve with maximum of 1. The minimum transmission point will appear in the resonating point ($\phi=\Omega T$). The numerical simulation is carried out based on the Phoenix Software package. The basic parameters for the simulated OAPF with loss are listed in Table I. The simulated power responses as a function of the wavelength for different values of the loss are presented in Fig.2. We can see that the power is equally 0.8 to different frequencies in the 0dB loss case. The value of the power response is 0.8 rather than 1 is mainly because of the 1-dB insertion loss (IL shown in Table I). For the lossy cases, the power transmission is lowest at the resonating point. We can also find that, the higher the loss is, the lower the power transmission is.

Table-I

Items	Value	Items	Value
c	0.707	ϕ	0
γ	0:0.5:1.5-dB	T	3.33-ps
s	0.707	IL	1-dB

Table I: Basic simulation parameter

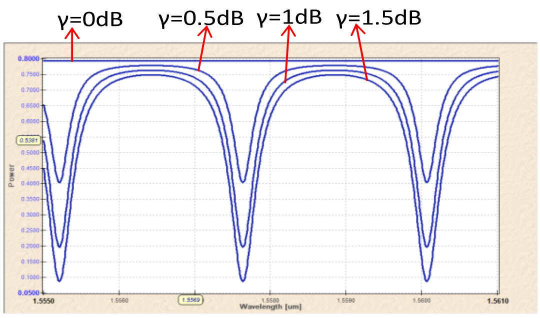

Fig.2 Power response of OAPF with loss

C. Group delay function of an OAPF with loss

The filter's group delay is defined as the negative derivative of the phase of the transfer function with respect to the angular frequency as follow:

$$\tau_n = \frac{d}{d\Omega}\tan^{-1}\left[P(Z)\right]_{z=e^{j\Omega T}} = \frac{P'(e^{j\Omega T})}{1+P^2(e^{j\Omega T})}, \qquad P(e^{j\Omega T}) = \frac{\mathrm{Im}(H(e^{j\Omega T}))}{\mathrm{Re}(H(e^{j\Omega T}))} \tag{6}$$

In the lossless case (γ=1), the group delay response can be expressed as below:

$$P(e^{j\Omega T}) = \frac{(1-c^2)\sin(\phi+\Omega T)}{2c-(1+c^2)\cos(\phi+\Omega T)}, \qquad \tau_n = \frac{P'(e^{j\Omega T})}{1+P^2(e^{j\Omega T})} = \frac{(1-c^2)T}{1+c^2-2c\cos(\phi+\Omega T)} \tag{7}$$

Now we look into the expression for the lossy case ($\gamma\neq1$). The core function P is expressed as below:

$$P(e^{j\Omega T})=\frac{0.5*c\gamma(\gamma-1)\sin[2(\phi+e^{j\Omega T})]+c^2(1-\gamma)\sin(\phi+e^{j\Omega T})+(1-c^2)\sin(\phi+e^{j\Omega T})}{-c+0.5*c\gamma(\gamma+1)+0.5*c\gamma(\gamma+1)\cos[2(\phi+e^{j\Omega T})]+2c-\gamma(1+c^2)\cos(\phi+e^{j\Omega T})} \quad (8)$$

It is obvious that the additional terms $0.5*c\gamma(\gamma-1)\sin[2(\phi+e^{j\Omega T})]+c^2(1-\gamma)\sin(\phi+e^{j\Omega T})$ in the numerator and $-c+0.5*c\gamma(\gamma+1)+0.5*c\gamma(\gamma+1)\cos[2(\phi+e^{j\Omega T})]$ in the denominator will introduce the variation for the final result. This variation is investigated by simulations. The simulations are carried out based on the parameters presented in Table-I as well. As shown in Fig.3, the group delay responses for different losses (0dB to 1dB) are similar. This indicates that the variation induced by the additional terms do not contribute much to the group delay with the loss in the considered range. The curves of the power responses and group delays are both presented in Fig.4 for comparison. We can see that the group delay values remain similar when the power responses vary from 0.8 to 0.2. This means that the amplitude can be controlled independently of the group delay.

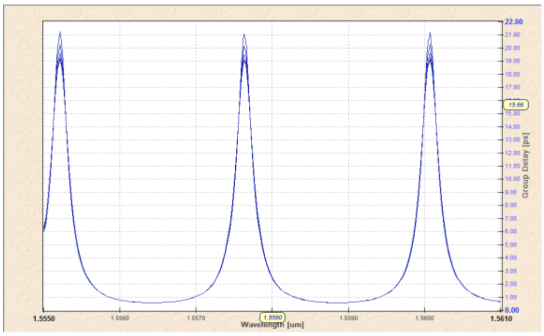

Fig.3: Basic simulation parameter

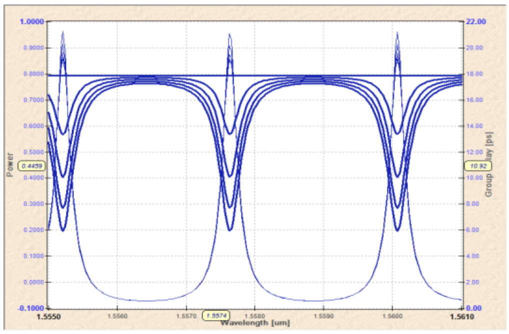

Fig.4 Power response of OAPF with loss

IV. Conclusion

In this paper, the optical all-pass filter with loss is theoretically investigated and numerically simulated. According to the theoretical analysis, the loss inside the ring will reduce the power transmission especially when the frequency is close to the resonant frequency. The simulation results goes well with our analysis. For the group delay, the loss induced variation is investigated by simulation. It shows that the group delays are quite constant when the loss varies from 0dB to 1dB. It means the amplitude can be controlled when the group delay is fixed. All the features show that the amplitude and group delay of the proposed optical all-pass filter based on a loss-controlled micro-ring resonator can be controlled independently.

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