Design and Simulation of a Compact All-Optical Differentiator Based on Silicon Microring Resonator

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ABSTRACT

In this paper, a compact all-optical temporal differentiator has been designed based on a silicon micro-ring resonator with a radius of 4 µm. In fact, by design of the silicon micro-ring resonator in the critical coupling region, calculation of first order derivative of the optical field has been realized. The operation of this optical differentiator has been simulated using a triangle pulse input. It is a compact optical circuit and is compatible with silicon-on-insulator (SOI) based optical integrated circuits.

Keywords - All-optical temporal differentiator, Silicon micro-ring resonator, Silicon-on-insulator (SOI)

I. INTRODUCTION

All-optical signal processing technology is a perfect solution to overcome the limitations of bandwidth and speed in electronic devices. The purpose of this technology is designing photonic devices equivalent of electronic devices. Using optical differentiators, as basic blocks for the realization of all-optical signal processing technology, the derivative of optical field’s envelope can be obtained [1]. Several designs for the realization of all-optical differentiators have been presented. Some of these designs have large physical size and as a result, the design of compact integrated circuits using them is not possible, and some of them have low-speed performance [2]. Therefore, in this paper, a photonic differentiator based on silicon ring resonator with a radius of 4 micron has been designed. The performance of differentiator is simulated by a triangular input pulse.

II. DIFFERENTIATOR DESIGN

Fig. 1 shows the structure of the resonator ring with a radius of 4 micrometer.

Fig. 1. All-pass ring resonator with a radius of 4 µm.

Transfer function of this all-pass ring resonator is [3]:

\[
T(\omega) = \frac{i(\omega - \omega_0) + \frac{1}{\tau_i} - \frac{1}{\tau_e}}{i(\omega - \omega_0) + \frac{1}{\tau_i} + \frac{1}{\tau_e}}
\]
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(1)

Where \( \omega_r, \tau_l \) and \( \tau_e \) are resonant frequency, time constant of internal losses of resonator and time constant of coupling losses between ring and waveguide respectively.

By designing ring resonator in the critical coupling region, i.e. realization of \( \tau_l = \tau_e \) and considering operating frequencies very close to resonant frequency, i.e. realization of \( \omega - \omega_r \ll BW_{2dB} \), resonator transfer function becomes as follows:

\[
T(\omega) = i\tau(\omega - \omega_r); \quad \frac{1}{\tau} = \frac{1}{\tau_l} + \frac{1}{\tau_e}
\]  

(2)

Given that equation (2) is equal to derivative in the time domain, it can be claimed that all-pass ring resonator under these conditions will play the role of first-order differentiator [2]. Those ring resonators which play the role of first-order differentiator, have phase shift equal to \( \pi \) in resonant frequency.

III. SIMULATION AND ANALYSIS

All of the parameters for full wave simulation of this all-pass ring resonator are shown in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{in} )</td>
<td>3.843 [µm]</td>
<td>Inner Radius</td>
</tr>
<tr>
<td>( R_{out} )</td>
<td>4.243 [µm]</td>
<td>Outer Radius</td>
</tr>
<tr>
<td>Gap</td>
<td>0.1 [µm]</td>
<td>Gap between ring and waveguide</td>
</tr>
<tr>
<td>width</td>
<td>0.4 [µm]</td>
<td>Width of ring and waveguide</td>
</tr>
<tr>
<td>( L )</td>
<td>12 [µm]</td>
<td>Length of waveguide</td>
</tr>
<tr>
<td>( n_1 )</td>
<td>3.478</td>
<td>Refractive index of core (Si)</td>
</tr>
<tr>
<td>( n_2 )</td>
<td>1.455</td>
<td>Refractive index of cladding (SiO(_2))</td>
</tr>
</tbody>
</table>

Table 1. Ring resonator and coupled waveguide simulation parameters.

Full wave simulation of all-pass ring resonator using finite element method (FEM) has been performed and the transfer function spectrum has been achieved as shown in Fig. 2. As can be seen, the resonant wavelength of this resonator is 1.55 µm. On the other hand, drop in the transfer function curve in this wavelength is equal to -46 dB. Therefore, the critical coupling region has been realized. The electric field of the resonator for 1.55 µm is shown in Fig. 3. According to the equation (1) and Fig. 3 and due to achieving critical coupling, output light of waveguide at the resonant wavelength 1.55 µm has approached to zero. Because of realization of critical coupling condition of resonator, if wavelength of the light is chosen very close to the resonance wavelength, the resonator will play the role of a first-order differentiator.

![Fig. 2. All-pass ring resonator transfer function.](image-url)
In order to achieve more detailed analysis of differentiation behavior of the resonator, triangular input pulse which is shown in Fig. 4, as envelope of sinusoidal signal with specified period has been considered. Due to ease of doing simulations in the frequency domain, time domain input signal should be transformed into frequency domain using Fourier transform and then obtained spectrum is applied to input terminal of the structure. According to the Fourier transform:

\[ f(t) = x(t)e^{i\omega_1 t} \rightarrow F(\omega) = X(\omega - \omega_1) \]  \hspace{1cm} (3)

Where \( \omega_1 \) has been chosen very close to \( \omega_r \). Thus, input signal Fourier transform can be obtained as following:

\[ X(\omega) = \frac{AT}{2} \sin^2 \left( \frac{\omega T}{4\pi} \right) \]  \hspace{1cm} (4)

\[ F(\omega) = \frac{AT}{2} \sin^2 \left( \frac{(\omega - \omega_1)T}{4\pi} \right) \]

Where A, T and \( \omega_1 \) are input signal amplitude, input pulse period and angular frequency close to resonance respectively. Spectral curve of triangular input pulse, i.e. \( F(\omega) \), taking into account the input pulse period equal to 160 picoseconds, has been plotted in Fig. 5. According this figure, in frequency domain simulation, assumed condition \( \omega - \omega_r \ll BW_{\text{fig}} \) is met.

In fact just input frequencies close to the resonant frequency, i.e. represented operating region in Fig. 5, has been applied to the structure.
After performing the simulation in the frequency domain, resulting output using an inverse Fourier transform has been converted to the time domain. Figures 6 and 7 represent input pulse envelope and its derivative in time domain respectively. According to these results, applied input pulse envelope to the resonator in time domain (Fig. 6) is not exactly the same represented triangle pulse envelope in Fig. 4; where this slight difference is due to the error of choosing the proper frequency range in condition $\omega - \omega_r \ll BW_{\text{res}}$. Furthermore, quasi-rectangular pulse shown in the Fig. 7 favorably represents the derivative of the input pulse envelope in Fig. 6 and its accuracy can be increased by reducing error related to the selection of the appropriate frequency range in condition $\omega - \omega_r \ll BW_{\text{res}}$.
IV. CONCLUSION

In all-optical computers in order to achieve high-speed signal processing, we need an all-optical integrator. By design and simulation of all-optical compact differentiator based on silicon ring resonator, we have taken a step in this direction. Compactness, all-optical and compatibility with the technology of optical integrated circuits based on silicon-on-insulator (SOI) are advantages of differentiator simulated in this article. Low bandwidth is the limitation of the simulated structure. Using the principles of circuit design and using differentiator in a feedback loop, we can provide an optical integrator that can be done in order to further research of this article.

REFERENCES

[1] Liu, Fangfei, Tao Wang, Li Qiang, Tong Ye, Ziyang Zhang, Min Qiu, and Yikai Su, Compact optical temporal differentiator based on silicon microring resonator, Optics Express 16, no. 20, 2008, 15880-15886.