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طراحی و شبیه‌سازی انتگرال‌گیر نوری

عباس دستجانی فراهانی، یاسمین رحیم اف*، حسن غفوری فرد، حمیدرضا حبیبیان

دانشکده فیزیک و مهندسی انرژی، دانشگاه صنعتی امیرکبیر، تهران، ایران. habibiyan@aut.ac.ir

چکیده – پردازش سیگنال فتونیکی به عنوان یک راهکار برای غلبه بر محدودیت ذاتی سرعت همتای الکترونیکی آن ارائه شده است. انتگرال‌گیر فتونیکی یکی از بلوک‌های اساسی پردازش سیگنال فتونیکی است. اخیرا پیاده‌سازی انتگرال‌گیر فتونیکی زمانی برپایه رزوناتورهای حلقوی به طور گسترده مورد بررسی قرار گرفته است. یکی از پارامترهای اساسی انتگرال‌گیرهای فتونیکی، زمان انتگرال گیری می‌باشد. در این مقاله ابتدا یک رزوناتور حلقوی با شعاع ۳ میکرون از جنس سیلیکون به عنوان انتگرال‌گیر فتونیکی طراحی شد، سپس با استفاده از روش بهینه سازی تاگوچی با تغییر ابعاد رزوناتور شامل شکاف، پهنا و ارتفاع موجبرها در ۵ سطح مختلف سعی در بهبود زمان انتگرال‌گیری شد و در نهایت بهینه زمان انتگرال‌گیری ۱۳٫۱ پیکو ثانیه بدست آورده شد.

کلید واژه– انتگرال‌گیر فتونیکی، بهینه سازی تاگوچی، پردازش سیگنال فتونیکی، رزوناتور حلقوی، زمان انتگرال‌گیری.

Design and simulation of optical integrator

Abbas Dastjani Farahani, Yasmin Rahimof*, Hassan Ghafori Fard, Hamid Reza Habibiyan

Physics and Energy Engineering Department, Amirkabir University of Technology, Tehran, Iran.
habibiyan@aut.ac.ir

Abstract- Photonic signal processing has been considered a promising solution to overcome the inherent speed limitations of its electronic counterparts. Photonic integrator is one of the fundamental blocks of photonic signal processing. Recently, the implementation of a photonic temporal integrator has been widely investigated, such as the implementation using a ring resonator. One of the most important characteristic parameters of a photonic integrator is the integration time. In this paper, a silicon ring resonator with a radius of 3 microns was designed as a photonic integrator, then by using the Taguchi optimization method and changing the resonator dimensions including the gap, width and height of waveguides in 5 different levels were tried to improve the integration time; finally the optimal integration time was achieved 13.1 ps.

Keywords: Integration time, Photonic integrator, Photonic signal processing, Ring resonator, Taguchi optimization.

1. Introduction

One of the prime drawbacks associated with digital signal processors is their limited operational speed, which in fact is restricted by their sampling rate. Also, with recent advancements in optical communication systems and optical network developments, which are chiefly based on digital signal processors, optical to electrical converters, and electrical to optical converters, such problems could increase losses within the system and be a burden to real-time processing. One of the best solutions to tackle these drawbacks and overcoming electron inherent speed limitations is to deploy Photonic Signal Processing (PSP) techniques. PSP systems tend to directly process digital signals in the optical domain, which makes it more cost-efficient, increases the processing speed, and raises the processor's power gain. Optical integrators are a type of device that integrates the input signals, which can be used in dark soliton production, optical memories, and analog to optical digital transducers. Capacitors are electrical surrogates of optical integrators. The main purpose of optical integrators is to trap the light within their structure. One of the main parameters of photonic integrators is integration time. An ideal photonic time integrator should have an infinite integration time. Most recently, time integrator implementation based on photonic techniques using Fiber Bragg Grating (FBG) [1-5], and Ring Resonators (MRR) [6, 7] are widely studied and investigated.

2. Methodology

2.1. Optical integrator principals

The frequency response of ring resonator is defined in Eq. 1 [7]:

$$\frac{1}{j(\omega-\omega_0)}$$

Where, ω_0 is the signal's central frequency, this response is defined in the time domain as below in Eq. 2:

$$u(t)=\begin{cases}0\rightarrow t\leq 0\\ 1\rightarrow t\geq 0\end{cases}$$

If the input central pulse frequency is equal to one of the resonance signals, and the pulse width in the time domain is greater than the time over which the light revolves a full circle in the resonator, the resonator's output will act as an optical integrator.

2.2. Design and simulation of ring resonator

In this study, for the purpose of simulation, Lumerical software and FDTD method have been deployed. The proposed structure consists of a Silicon Dioxide surface and Silicon straight and ring waveguides on placed on it. The proposed structure could be observed in Fig. 1.

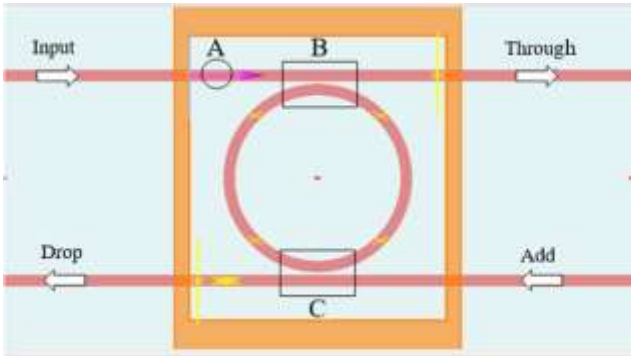

Fig. 1: Ring resonator simulation with a radius of 3 micron.

According to Fig. 1, the structure consists of two straight and one ring waveguides. The input pulse is generated via Mode source (A), and through the upper waveguide's Input port enters the structure. A fraction of light is coupled with the ring waveguide at point (B), and the other fraction keeps on moving forward until exits from the upper waveguide's Through port. A fraction of coupled light with the ring again couples with the lower waveguide at point (C) and exits from Drop port. In order to obtain the output spectrum and light's time diagram, power monitor and time monitor are deployed at Drop port, respectively. Moreover, for obtaining the quality factor at Drop port and the ring itself, Q analysis has been taken advantage of.

As it is explained, a ring resonator could function as an optical integrator is the input pulse's central frequency equal to one of the resonance frequencies of the resonator. In this section, the simulation is performed with a source wavelength of 1500 to 1600 nanometres and the output spectrum and resonance frequencies are obtained. Thereafter, the closest resonance frequency to 1550 nanometres is measured and taken as the input pulse's central frequency. Also, the pulse width is set equal to the obtained FSR. Finally, the simulation is run again and integration time is calculated.

2.3. Taguchi optimization

In this study, the optimization process is carried out via Taguchi method in Minitab software environment. The optimization is performed in 5 levels in order to attain the optimum integration time. The Taguchi method optimization levels are opted with respect to several simulations, and trial and error. For instance, if the width and height of the waveguide exceed their upper bond values, the light would get trapped within the input straight waveguide and thus wouldn't couple with the ring waveguide. Also, if the width and height of the waveguide aren't larger than their lower bond values, the optical losses will soar and light penetrates outside the waveguide. Furthermore, if the gap exceeds a certain value, the coupling will not happen between the straight and ring waveguides. With respect to the explained elaborations regarding the resonator's geometrical restrictions, the Taguchi optimization levels are enlisted in table 1, where all measurements are in nanometres.

Table I. Ring resonator optimization parameters

Level	Gap (nm)	Width (nm)	Height (nm)
1	50	320	150
2	100	400	180
3	150	420	200
4	200	450	220
5	250	480	250

After selecting the optimization variables (decision variables) and the number of levels, the Taguchi experimental design method would plot several experiments to simulate. Since in this study there are 3 decision variables and 5 levels, Taguchi method proposes 25 experiments to be simulated. After running the simulations and importing their results in Minitab software, an optimization graph as seen in Fig. 2 would be yielded. This graph demonstrates the optimum value for integration time with respect to designed experiment by Taguchi method.

3. Result and Discussion

As mentioned before Fig. 2 is the Taguchi optimization output in this study. It could be elicited that opting a gap value equal to 4th level will result in the maximum signal to noise ratio. Hence, in the final optimum structure simulation, gap should be chosen from the 4th level. As evident from Fig. 2, in the final optimum structure, width and height of the resonator should be opted from the 5th level, which has the maximum signal to noise ratios for both variable. Finally it could be concluded that with a gap of 200, height of 250, and width of 480 nanometres, the optimum integration time would be achieved.

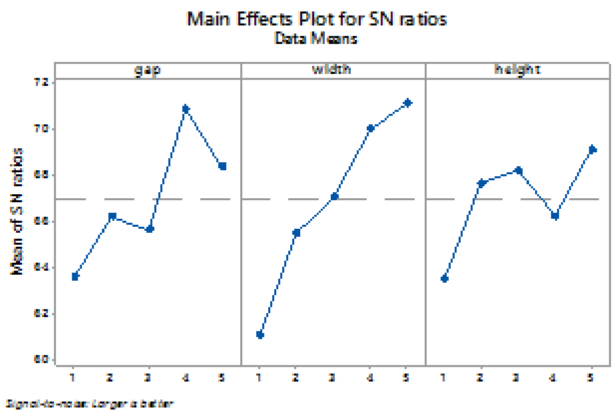

Fig. 2: Taguchi optimization graph for a ring resonator with a radius of 3 micron

Thereafter, the optical integrator of interest is finally simulated with the obtained optimum dimensions, and the integration time parameter is evaluated. With the optimum dimensions, an integration time of 13.1 ps is attained. Fig. 3 illustrates the integration time of the optical integrator.

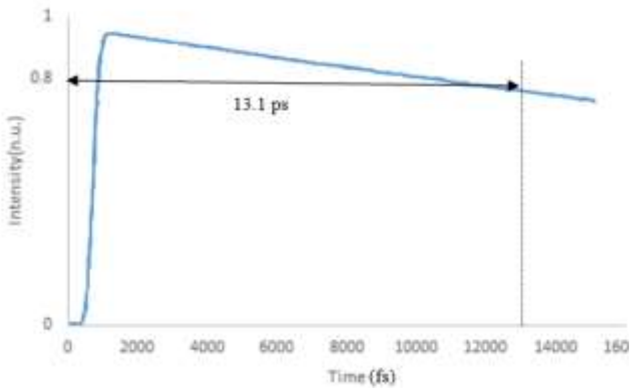

Fig. 3: Integration time of the optimized ring resonator.

Results of the optimized optical integrator are compared with that of Ferrera et al. [7] study and reported in Table II.

Table II. Comparison between the present study and the study conducted by Ferrera et al [7]

	Ferrera et al. [7]	**Present study**
Ring radius	47.5 µm	3 µm
Integration time	12.5 ps	13.1 ps
Power gain	1.5%	2.9%
FSR	575 GHz	3652 GHz

As it could be seen in Table II, the ring resonator's radius has been drastically decreased from 47.5 microns to 3 microns. It is expected to have a significant drop in quality factor and integration time with miniaturizing the resonator's dimensions. Conversely, in this study, with miniaturizing the ring, not only didn't the integration time decline but slightly rose. Furthermore, power gain and FSR parameters are improved compared with Ferrera's et al. [7] study.

4. Conclusion

Designing an optical integrator and optimizing its important parameters so-called power gain, integration time and FSR were the aim of this research. In this study, first, we model a ring resonator with a radius of 3 microns as an optical integrator. Next, by using the Taguchi experimental design method and altering geometrical design variables including the gap, width and height of waveguides, it has been tried to optimize the optical integrator's main parameters. Finally, the optimum integration time amounted to 13.1 ps. Also in this study, the outcome of power gain is 2.9% with an FSR of 3652 GHz. According to the simulation results, it has been concluded by miniaturizing the optical integrator, most important parameters namely integration time, power gain, and FSR have been improved.

References

[1] R. Slavík et al., "Photonic temporal integrator for all-optical computing," Optics express, vol. 16, no. 22, pp. 18202-18214, 2008.p

[2] M. H. Asghari and J. Azaña, "Design of all-optical high-order temporal integrators based on multiple-phase-shifted Bragg gratings," Optics express, vol. 16, no. 15, pp. 11459-11469, 2008.

[3] M. H. Asghari and J. Azaña, "On the design of efficient and accurate arbitrary-order temporal optical integrators using fiber bragg gratings," Journal of Lightwave Technology, vol. 27, no. 17, pp. 3888-3895, 2009.

[4] C. Wang, J. Yao, and J. Azaña, "High-order passive photonic temporal integrators," Optics letters, vol. 35, no. 8, pp. 1191-1193, 2010.

[5] Y. Park and J. Azaña, "Ultrafast photonic intensity integrator," Optics letters, vol. 34, no.8, pp. 1156-1158, 2009.

[6] M. Ferrera et al., "On-chip CMOS-compatible all-optical integrator," Nature Communications, vol. 1, p. 29, 2010.

[7] M. Ferrera et al., "All-optical 1st and 2nd order integration on a chip," Optics express, vol. 19, no. 23, pp. 23153-23161, 2011.

[8] W. Liu et al., "A fully reconfigurable photonic integrated signal processor," Nature Photonics, vol. 10, no. 3, p. 190, 2016.