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SpliESR: Tunable Power Splitter Based on an Electro-Optic Slotted Ring Resonator

Rajib R. Ghosh [a], Janib Bashir [b], Smruti R. Sarangi [b], Anuj Dhawan [a,*]

[a] *Department of Electrical Engineering, Indian Institute of Technology Delhi, New Delhi, India*
[b] *Department of Computer Science & Engineering, Indian Institute of Technology Delhi, New Delhi, India*

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ABSTRACT

In this paper, we present a novel optical power splitter having an arbitrary split-ratio that can be tuned over a wide range by employing relatively low voltage levels. It is based on a slotted ring resonator. A 120 nm electro-optic polymer-filled slot is created throughout the circumference of the ring. The hybrid ring resonator is made to work between the full and off resonance states, allowing it to work as a power splitter. This is done by changing the refractive index of the electro-optic polymer inside the slot by the application of an external electric field. The splitter combines the electro-optic functionality of the polymer with the high index contrast of the silicon, resulting in a low tuning voltage power splitter. Over a small voltage range of 0–1 V, it is possible to change the split-ratio of this splitter from 0.031–16.738, making it 10 times better than other competing designs. In addition, it takes less than 500 ps to reconfigure the splitter.

1. Introduction

The performance and scalability of workloads running on many core chips is often constrained by the performance and available bandwidth of the underlying Network-on-Chip (NoC). A conventional NoC is an electrical network with tens of buffers, virtual channels, and routers with multi-cycle propagation delays. Due to these limitations, researchers have explored the use of nanophotonics for developing fast on-chip networks [1]. In the last decade, industry and academia have accelerated their work in developing efficient nanophotonic networks [2–4].

In most of the nanophotonic interconnects, the optical power from the off-chip laser is routed through a single waveguide, called the backbone waveguide, to all the optical stations in the network [5]. Each station is associated with an optical component, called power splitter, which splits some portion of light from the backbone waveguide for its own use. The amount of power diverted from the power waveguide depends upon the split-ratio of the power splitter. In our manuscript, we are defining the split ratio as the ratio of the drop port power and the through port power.

Traditionally, optical power splitters have primarily been based on multimode interference (MMI) [6], Y junctions [7] and directional couplers (DC) [8]. Normally, these splitters have a predefined split-ratio and hence, always divert the same amount of power from the backbone waveguide, irrespective of the need of an optical station. This results in an increased power loss. To decrease such power losses, most of the proposals divide the total execution time into fixed size durations called epochs [5]. At the end of every epoch, they predict the amount of laser power required by each optical station and the associated split-ratio of the power splitters and then modulate the laser accordingly. However, to realize this aim, we require the power splitters with a free choice of splitting ratio. There are many previous works aiming at developing tunable power splitters, such as electro-optic MMI based splitters [9], and p–n junction ring resonator based splitters [10]. However, we require splitters with a wide tuning range and a lesser reconfiguration time, because the splitters cannot be used while they are being reconfigured. The previously described splitters have a reasonable split range, but they take more than 10 cycles (@ 2 GHz) to reconfigure [11]. The p–n junction splitter can be reconfigured in a single cycle, but has a shorter tuning range [10]. Thus, we require a splitter that can be quickly reconfigured and has a wide tuning range. In this paper, we provide one such solution by proposing a novel splitter, called SpliESR with a reasonable tuning range and a lesser reconfiguration time.

SpliESR is a hybrid structure of an electro-optic (EO) polymer and a ring resonator. The choice of the EO polymer is based on the presence of the Pockels effect in such polymers. As a result, they can be tuned much faster. Moreover, due to the higher value of Pockels coefficients (>300 pm/V) [12–14] in such polymers, it is possible to change their refractive index significantly under an applied electric field. Keeping this in mind, we created a small sized slot, filled with an EO polymer, inside the ring resonator. This hybrid structure is allowed to work between full and off resonant states based on the applied electric field. At lower voltages, the refractive index of the electro-optic polymer

* Corresponding author.
E-mail address: adhawan@ee.iitd.ac.in (A. Dhawan).

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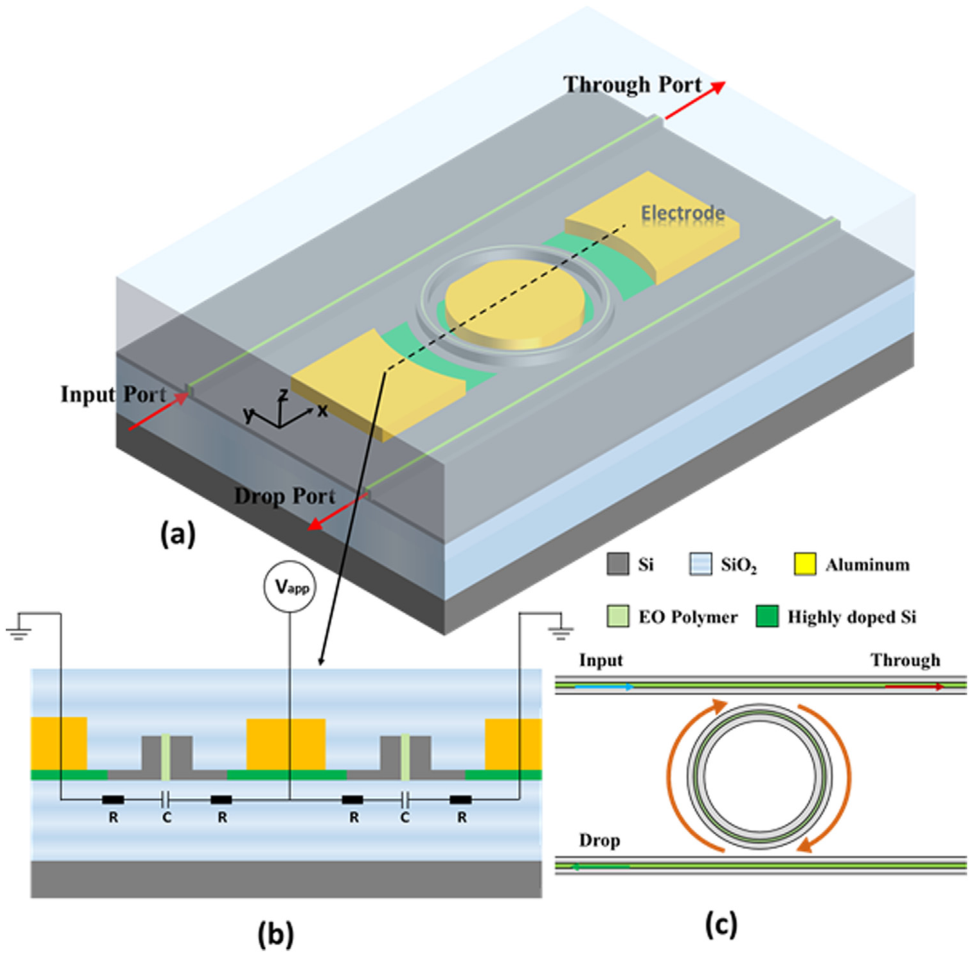

Fig. 1. (a) Schematic of the proposed tunable power splitter. The slot is filled with an electro-optic (EO) polymer in the silicon strip waveguide. The structure is covered with SiO_2. (b) Equivalent electrical circuit of the power splitter in the plane bisecting the ring. (c) The top view of the proposed structure.

remains unaffected and the resonator works at the full resonant state, allowing almost all the power to pass through the drop-port (ring-resonator details are shown in Fig. 1). Increasing the voltage, changes the applied electric field, which in turn induces the change in refractive index of the EO polymer at the center of the ring. This results in variation in the ratio of the power passed along the drop and through ports. We carried out the device simulations of this hybrid structure using a device solver, and subsequently a FDTD solver [15,16]. We demonstrated that for a voltage range of 0–1 V, we can achieve the tuning range of 0.031–16.738 in a single cycle.

2. Device concept

In this section, we describe the basic device concepts related to the ring resonators and the electro-optic polymers. When the light propagates through the microring resonator, it filters out one specific wavelength (resonant wavelength (λ_r)) from the input waveguide and guides it through the drop channel. The resonant wavelength depends on the radius (R) and the effective refractive index (n_{eff}) of the ring resonator as given by Eq. (1).

$$\lambda_r = \frac{2\pi R n_{eff}}{m} \tag{1}$$

The resonator is made to work in the resonant state whenever we want to filter out the resonant wavelength from the input waveguide. However, when we want to allow the wavelength to pass along the through port, the resonator is brought out of the resonant state by changing its effective refractive index. Thus, it can be used as a switch where it is allowed to work in two different states: the on state and the off state.

However, to make it work as a power splitter, it is required to make the resonator operate between these two states. This can be done by changing the refractive index of the ring resonator in small steps. There are two main ways of changing the refractive index of the silicon based ring resonator: by changing the temperature of the ring (thermo-optic) [17] or by changing the carrier concentration [18] inside the ring. Peter et al. [10] have proposed a splitter based on the similar principles where they tune the ring resonator by changing its carrier concentration and by changing the temperature. However, both these mechanisms have limitations. The thermo-optic effect is limited by the switching time [17] and the carrier injection is limited by the carrier life time [18] (and limited by a narrow split range).

Due to some intrinsic advantages of EO polymers such as large electro-optic coefficient, short response time, low dielectric constant, and good compatibility with other materials [19], they are considered as the possible alternative to the silicon based modulators. It is possible to drive such modulators at very low voltages and provide high band-width [20,21]. One important characteristic of EO polymers is that they show a significant change in the refractive index (due to high Pockels coefficients) in presence of an external electric field. The refractive index change (Δn) is given by Eq. (2):

$$\Delta n = \frac{\Gamma r_{33} n_p^3 E}{2} = \frac{\Gamma r_{33} n_p^3 V}{2W_{slot}} \tag{2}$$

where E is the applied electric field, V is the voltage, n_p is the electro-optic polymer refractive index, r_{33} is the electro-optic coefficient of the polymer (~430 pm/V), Γ is the overlap factor (~0.21) and W_{slot} is the width of the electro optic polymer filled slot. Thus, under an applied electric field, the EO polymer refractive index varies linearly with the voltage applied.

Our novel concept of using a hybrid structure of a slotted silicon ring resonator and an EO polymer to design an optical power splitter is shown schematically in Fig. 1(a). The main idea behind our approach is to utilize the high electro-optic effect in EO polymers to change the effective refractive index of the ring resonator under an applied electric field. Fig. 1(b) shows the cross-sectional view of the device and the equivalent electric model. We start with a silicon on insulator (SOI) substrate. It consists of a thin silicon layer on top of a 2 μm oxide layer (SiO_2). The silicon strip waveguide ring resonator of radius 50 μm is present above the silicon layer. The silicon layer has a background doping which is n-type, with highly doped n+ regions around the ring. The ohmic contacts (electrodes) are provided with these highly doped regions in order to decrease the resistance while applying the electric voltage. A 120 nm slot is created at the center of the silicon waveguide. The slot is completely filled with the electro-optic polymer.

The silicon waveguide has a cross-section of 500 nm × 220 nm with a coupling gap (G) of 100 nm. In order to reduce the overlap of the optical field inside the ring with the highly doped regions, and to provide highly lateral confinement of optical field, it is recommended to have a silicon slab of thickness less than 50 nm [22]. We have assumed a thickness of 30 nm in our design. The highly doped regions should be far enough from the silicon waveguide in order to reduce the absorption loss but short enough for lesser switching time and power consumption. In our case, the distance between silicon rib waveguide and the highly doped regions is 400 nm. Note that the slotted ring resonator is covered with a coating layer of SiO_2 material. The proposed power splitter is operated in Transverse Electric (TE) mode. The optical mode is well confined in the slot as a result the modal volume is very less.

3. Results and discussion

3.1. Analysis of the slotted hybrid structure

For an efficient tunable optical power splitter based on an EO slotted ring resonator, we need a configuration with a low power loss and a relatively high overlap factor of the EO slotted waveguide. We carried out simulations to determine the optimal dimensions of the radius of the ring and of the width of the EO slot such that the power loss could be minimized and a high overlap factor could be obtained. Fig. 2 shows the variation of the optical power loss with a variation in the radius of the ring. It is clear from the figure that with an increase in the radius, there is a decrease in optical power loss. We can observe from Fig. 2 that having a ring radius greater than 50 μm provides low optical loss. As it is desirable to choose the lowest possible ring radius (for obtaining a more compact device) that has a low optical loss, 50 μm is the optimal radius and was chosen by us in the design of the tunable power splitter.

In our design of the electro-optic slotted ring resonator, we varied the slot width from 80 nm to 220 nm in order to determine the optimal values of the slot width in terms of the overlap factor and the optical loss. We calculated both the variation in the overlap factor and in the optical loss with a change in slot width, as shown in Fig. 3. It can be observed from Fig. 3 that with an increase in the slot width, there is a decrease in the optical loss. However, the overlap factor also decreases with an increase in slot width. Hence, there is a tradeoff between the optical power loss and the overlap factor of the slot. Thus, we have chosen an optimal slot width (120 nm) at which the optical loss is low and the overlap factor is high.

In addition, increasing the slot width also affects the shift in the resonance wavelength for an applied electric field. Fig. 4 shows the variation of the resonance wavelength and also the amount of shift in resonance per unit applied voltage with a variation in the slot widths. It can be seen from Fig. 4 that the shift of resonance wavelength due to

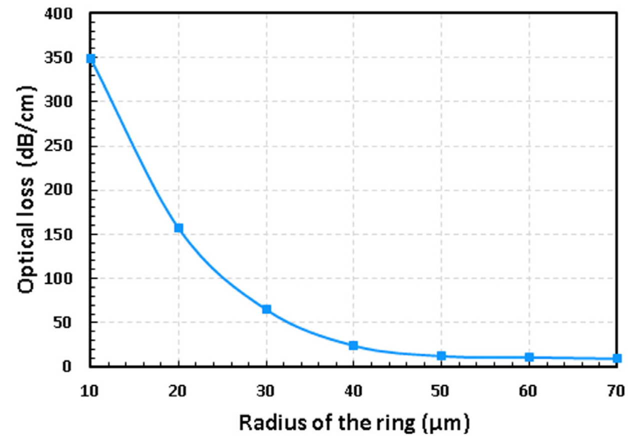

Fig. 2. Variation of the optical power loss with a variation in the radius of the ring in an EO slotted ring resonator. The slot width of the EO slotted ring resonator was taken to be 120 nm.

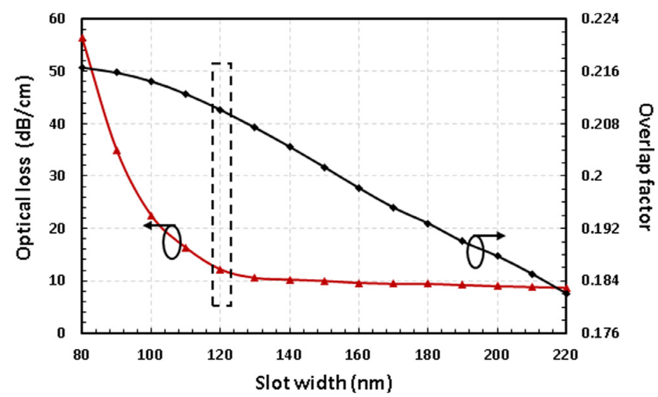

Fig. 3. Variation in the optical loss and overlap factor with a variation in the slot width in an EO slotted ring resonator. The radius of the ring was taken to be 50 μm.

the applied voltage is larger in smaller slot widths. Hence, by applying the same voltage for different slot widths, the maximum shift in the resonance wavelength occurs in the configuration with the least slot width. This is because the change in the refractive index of the slot increases with a decrease in slot width. Moreover, higher is the shift in resonant wavelength, wider is the tuning range (i.e. the split ratio). Thus, based on above analysis, we chose the 120 nm value as the slot width in our proposed splitter. Moreover, previous work has shown that it is possible to fabricate such smaller EO polymer filled slotted waveguides [23].

Fig. 5(a), (b) show the electric-field distribution (the optical electric-field distribution) for the full resonance mode and the off resonance mode. One can observe from the figure that a distinctive resonant-mode is formed in the slot at the resonance wavelength. The optical electric field profile inside a slot is shown in Fig. 5(c). Fig. 5(d) shows the electrical field due to applied external voltage. Both the figures show that most of the optical field and RF field is confined within the slot (see Fig. 5).

3.2. Analysis of the SpliESR

For our experiments, we use a device solver (Lumerical DEVICE) [15] for electrical simulations and a FDTD solver (Lumerical FDTD Solutions) [16] for optical simulations. The device solver is used to calculate the static electric-field distribution as a function of the applied static voltage (V_{app}), whereas the FDTD solver is used to calculate the variations in the effective refractive index of the ring resonator with

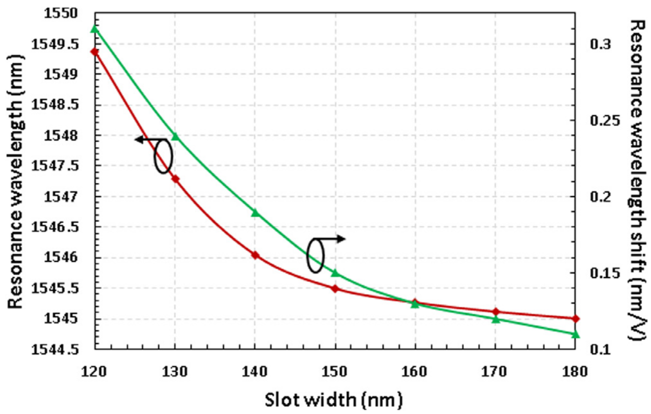

Fig. 4. Shift in the resonance wavelength with a variation in the slot width (left) and the total resonance wavelength shift (right) per unit applied voltage for different slot widths.

a change in the applied static electric field. In addition, it is used to calculate the changes in the resonant peak of the ring resonator with a variation in the effective refractive index. We started by modeling the splitter in a device solver. We ran a static voltage sweep and calculated the electric-field distribution inside the ring as a function of applied static voltage (V_{app}). The calculated electric field was imported in the FDTD solver in order to calculate the mode profile as well as the variation in the refractive index of the EO polymer as a function of the static electric-field. The variation in the polymer refractive index enables the resonator to work in between the on and off states. At 0 V, the ring resonator splits the entire light (@1549.37 nm) from the through channel resulting in a high split-ratio. However, at higher voltages the resonator is brought out of the resonant state, due to the change in the effective refractive index, resulting in a very low split-ratio. For the intermediate voltages, the resonator allows some light to pass along the through port and some portion is allowed to pass through the drop-port. In Fig. 6, we have plotted the variation in split-ratio of our design over a voltage range of 0–1 V. For a 120 nm slot, we are able to achieve the split-ratio tuning range of 0.031–16.738.

In Fig. 7, we plot the variation in the resonant peak of the ring resonator with a 120 nm slot as a function of a bias voltage. As the applied voltage is increased, corresponding effective refractive index also increases, resulting in the red-shift in resonance. Due to the small device dimensions, the interaction length is small as compared to RF wavelength. Therefore it can be electrically modeled by lumped elements. The equivalent electrical model in push–pull configuration is shown in Fig. 1(b). The silicon waveguide and slab is doped with n-type dopant with concentration of 1×10^{17} cm^{-3} and some portion is doped with concentration of 1×10^{20} cm^{-3} as shown in Fig. 1(a) and (b). Therefore, the splitter is limited by the time (R_{eff} C_{eff}) to charge the capacitor that is formed due to the slot. We have used Lumerical device solver to calculate the R_{eff} and C_{eff}. The theoretical bandwidth of the proposed device is $f_{3db} = 1/(2\pi R_{eff} C_{eff}) \approx 95$ GHz.

In electro-optic polymer based devices (such as modulators or power splitters) where an external voltage is used to change the effective refractive index of the device, the applied voltage gives a rough estimation of the external power consumed in changing the effective refractive index of the device. SpliESR can achieve much larger split-ratios (as well as a much larger range of split-ratios) using considerably smaller external voltages (less than 1 V) as compared to previously reported power splitters [10] that have employed much larger external voltages to achieve smaller values of split-ratios. Thus, the power splitter being proposed in this paper (SpliESR) consumes much less external power as compared to other state-of-art tunable power splitters. We calculated the power consumption of SpliESR using the Lumerical device solver. The power is calculated as 28 mW and maximum energy consumption of 21fJ at maximum applied voltage of 1 V.

We would like to mention that as ring resonators are very sensitive to changes in temperature, we need to employ mechanisms to stabilize the temperature in these resonators, as has been demonstrated previously by several researchers [24–26].

3.3. Reconfiguration time

The response time or reconfiguration time of the splitter depends upon: the response time of the EO polymer, optical stability of a ring resonator and the frequency of the voltage source. The EO polymers have ultra-short response time (less than 10 femtoseconds) [19] and the ring resonators take less than 50 ps to stabilize. For a voltage source, Digital to Analog convertors (DAC) are commonly used to generate the tuning voltages. Fig. 8(b) shows the schematic of the connection between microring resonator and DAC using cu metal interconnect. Many high speed DACs have been proposed which work at more than

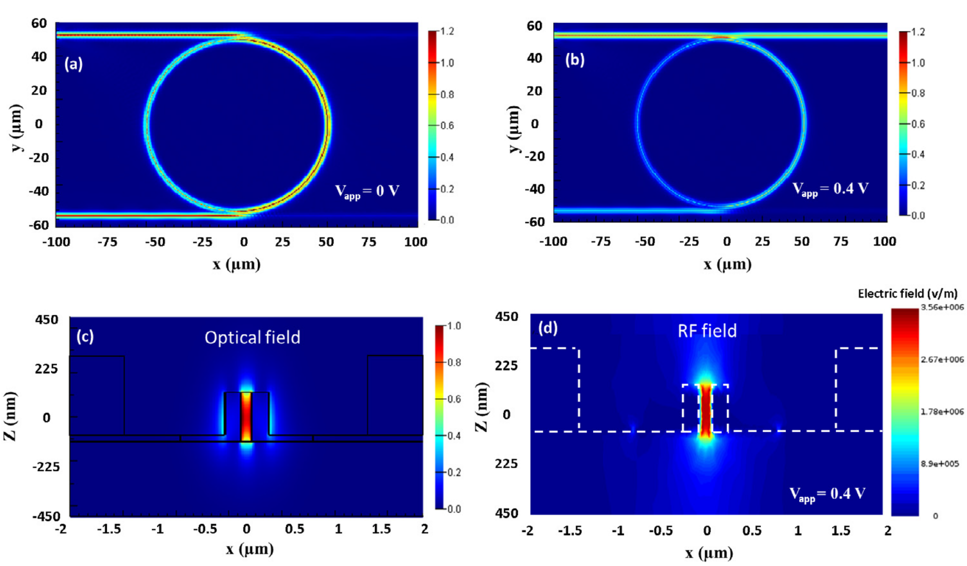

Fig. 5. Results of FDTD solver simulations showing the optical electric-field profile of the slotted hybrid microring resonator for (a) full resonance and (b) off resonance. (c) Optical electric-field profile of the slot at the resonance frequency. (d) Results of device solver simulations showing the static electric-field distribution at the cross-section of an electro-optic polymer-filled doped silicon slot ring, calculated for a constant applied voltage (V_{app}) of 0.4 V.

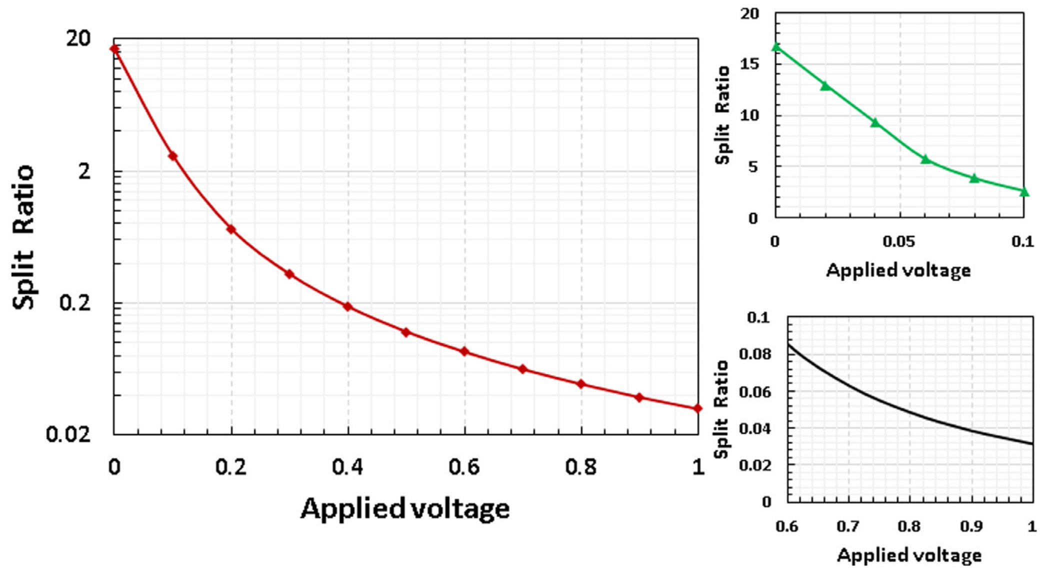

Fig. 6. The calculated split-ratio of the proposed tunable power splitter with a variation in applied voltage (plotted in log scale). The figures on the right show the regions of this plot when the applied voltage ranges from 0 V to 0.1 V and from 0.6 V to 1 V (plotted in linear scale).

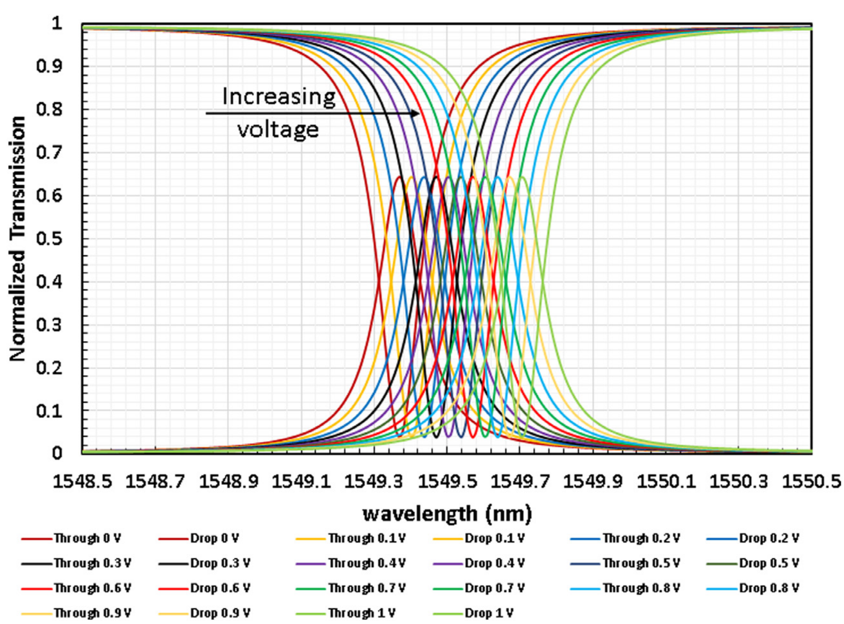

Fig. 7. The variation of the normalized transmission spectra (for the through-port and the drop-port) with applied voltage (V_{app}), showing a red-shift in the resonance wavelength when the applied voltage is increased.

20 GHz speed [27]. Considering the ring resonator as a capacitive load, these DACs can be used to generate the voltages at processor speeds (≈ 2 GHz). Thus, our splitter acts as an ultra-fast splitter with a reconfiguration time less than 500 ps. This reconfiguration time is limited by the fastest DAC.

The DAC is used to generate the tuning voltages for reconfiguring the splitter. Presently, we have 8-bit high speed DACs which are commonly available. As a result, it is possible to generate 256 different voltages using such a DAC. Thus, we have 256 different possible split-ratios. However, we cannot generate the split-ratio between any two consecutive possible split-ratios sr1 and sr2. Thus, if we want to use any such split-ratio, then the splitter is tuned to the nearest possible split-ratio. This error in split-ratio is limited to ($|sr2 - sr1|/2$). In Fig. 8(a), we plot the 'error in split-ratio' with the 'number of bits' required by the voltage-source. We plotted the average and maximum error across all the possible consecutive split-ratios for different bit DACs. It is clear from the figure that for a higher bit DAC, the error decreases significantly.

4. Conclusion

In summary, we propose a compact optical power splitter with a potential to achieve an arbitrary split-ratio, which can be tuned over a wide range of values. The device is a hybrid structure in which a nanoscale slot is created at the center of the ring resonator. An EO polymer is infiltrated in the slot. We have leveraged the high electro optic effects in EO polymers to achieve wide split-ratio tuning ranges at relatively lower voltages. The main principle behind the working of such a device is that we can change the refractive index of the polymer under an application of electric field, enabling the resonator to work as a power splitter. In addition, the short response time of the electro-optic polymer allows the device to achieve lower reconfiguration time. Based

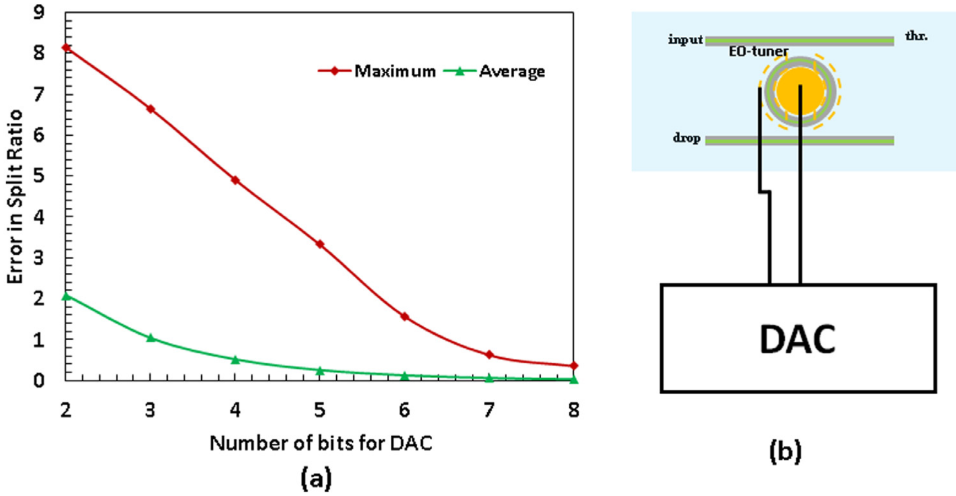

Fig. 8. (a) The calculated error in split-ratio of the proposed tunable power splitter with a number of bits for DAC. (b) Schematically showing a micro ring resonator connect with a DAC using a high speed transmission line (such as a copper interconnect).

on our proposed structure, a split-ratio tuning range of 0.031–16.738 is achieved over a voltage range of 0–1 V. In addition, it is possible to reconfigure the splitter in less than 500 ps.

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