Original architecture of an efficient all-optical 2×4 photonic crystals decoder based on nonlinear ring resonators

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Abstract
In this paper, we have presented an efficient original architecture of all-optical 2×4 photonic crystal decoder based on non-linear ring resonators. The fundamental structure is a square lattice of 2D GaAs rods, operating around the wavelength 1.55 µm. The proposed decoder is composed of a combiner with three input ports, where the port E is used for excitation and A1, A2 are the control ports, and an optical switch with four output ports, and it is a nonlinear DMEX. For the creation of a switch at the wavelength of 1.55 µm, we used nonlinear chalcogenide glass rods with a nonlinear Kerr coefficient equal to 9×10⁻¹⁷ m²/w. The switching intensity and structure size are 1 Kw/µm², 27.12 µm × 17.96 µm, respectively. The contrast ratio is about 8.7. The maximum crosstalk and insertion losses are calculated to be about −22.1 and −4.5 dB. The maximum and minimum power levels for logic states 0 and 1 are 0.05×P₀ and 0.37×P₀ where P₀ is the input power. The finite element method was used to perform the necessary calculations.

Keywords Photonic crystal · Ring resonator · 2×4 decoder · Nonlinear optic · Kerr effect

1 Introduction
The use of light as a transmission medium in fiber optic communication systems, responds to several obstacles that hinder the development of today’s telecommunications such as: transmission lines saturation, increase in data rates and noise elimination… etc. In recent years, science has been working to achieve all-optical communication that requires integrated optical networks based on optical devices for optical signal processing (Raghuwanshi and Kumar 2013; Kumar et al., 2017; Raghuwanshi et al., 2012), and which offer better noise immunity, higher data rates and high bandwidth processing capability (Mehdizadeh et al., 2017a; Serajmohammadi et al., 2015). The appearance of photonic crystals has created potential opportunities for the realization of all-optical devices that give potential solutions to speed limitations, power consumption, immunity to electromagnetic interference (Daghooghi et al., 2018a), and give the possibility to eliminate optical-to-electrical conversion and thus the information processing will become optical.

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Due to diffraction limitations, the standard manufacturing resolution of the far-field laser beam is half the laser beam wavelength. Therefore, one way to reduce the size of the elements is to reduce the wavelength of the laser. Studying light on a spatial scale smaller than its wavelength conventionally, the minimum scale on which a light beam can operate is equal to half its wavelength. However, by coupling light to matter, photonic effects can be realized on much smaller spatial scales (Li 2010).

Photonic crystals are nanostructured dielectric materials whose refractive index varies periodically over the wavelength range of light (Rostamizadeh et al. 2020). This periodicity causes the appearance of an optical property called photonic band-gap PBG where the transmission of light is totally forbidden (Delphi et al. 2019; Alipour-Banaei et al. 2014a). Materials with a periodic dielectric profile are called photonic band gap materials (PBG) or photonic crystals (PhC). As a result, they can block the propagation of light of certain frequencies or wavelengths in one, two or more polarization directions within the materials. Defects in a PBG will strongly affect the electromagnetic field. In these PBGs possess unique optical resonances and their properties can be customized through proper design of the band gap and the introduced defects. Thanks to the bandgap (PBG), several optical devices can be realized such as: optical filters (Rostamizadeh et al. 2020; Delphi et al. 2019; Alipour-Banaei et al. 2014a; Farah et al. 2016; Badaoui et al. 2011; Chaker et al. 2020), demultiplexers (Naghizade and Sattari-Esfahlan 2020; Mehdizadeha et al. 2016), logic ports (Mokhtari et al. 2020; Sharifi et al. 2017; Yan et al. 2019), adders (Neisy et al. 2018; Rahmani and Mehdizadeh 2018), analog-to-digital converters (Mehdizadeh et al. 2017b, c), encoders (Moniem 2016; Gholamnejad and Zavvari 2017), decoders (Parandin et al. 2018; Alipour-Banaei et al. 2014b; Daghooghi et al. 2018b) and splitters (Fedaouche et al. 2018; Fedaouche 2016)… etc.

Today, real fabrications of a photonic crystal structure have been made to prove the possibility or feasibility of realizing photonic devices. Such as, in Jiang et al. (2012) the authors proposed and fabricated a new 2D photonic crystal slab with large band gaps of high order in the near infrared wavelengths composed of a number of silicon rods and placed them in a unitary array of square cells. And in Ye et al. (2004), a photonic structure consisting of arranged dielectric honeycomb cylinders were fabricated in silicon using electron beam lithography and inductively coupled plasma dry etching which allowed to obtain and experimentally confirm the full photonic band gap in the vicinity of optical communication wavelengths around 1.5 µm.

To fabricate photonic crystal waveguides, the authors in Assefa et al. (2004) grew GaAs/Al0.9Ga0.1As heterostructures on GaAs substrates by gas-source molecular beam epitaxy. 300 nm SiO2 was then deposited on the substrate by sputtering. Photonic crystals are defined by scanning electron beam lithography using polymethyl methacrylate (PMMA) resist. PMMA is grown in a 1:2 solution of methyl isobutyl ketone (MIBK) and isopropanol (IPA). A 35 nm-thick nickel film was then evaporated onto the sample, and a thermal bath of 1-methyl-2-pyrrolidone (NMP) was used for the lift-off process. Nickel is used as a hard mask and the pattern is transferred into SiO2 by reactive ion etching (RIE) in CHF3 plasma. Remove the nickel mask in wet nickel etchant. Using a SiO2 mask, the authors etched GaAs and underlying Al0.9Ga0.1As in the BCl3 plasma for the dielectric rods to a total depth of 1.5 µm.

Optical combination and sequential devices are important elements of many information processing functions. Therefore, many scientists have tried to design all-optical decoders because they are important for logic systems used in optical communication networks (Daghooghi et al. 2018b). In Singh et al. (2017), the authors cascade MIM plasmonic waveguides to design a Mach–Zehnder interferometer (MZI) for the design of an
all-optical 38-line decoder. In Pal et al. (2018), the authors used the electro-optic effect in a Mach–Zehnder interferometer (MZI) to create 2–4 line and 3–8 line decoders based on lithium niobate. In Pal et al. (2017), Amrindra Pal, Santosh Kumar and Sandeep Sharma proposed a seven-segment decoder based on the electro-optic effect in MZI and lithium niobate. Design multiple all-optical structures using the MZI as it is capable of switching the optical signal to the desired output port (Singh et al. 2017; Pal et al. 2017, 2018).

In Serajmohammadi et al. (2015) and Mehdizadeh et al. (2017d) the authors used a non-linear resonant ring in a square array as a fundamental structure for the realization of a 1 × 2 decoder, such that in Mehdizadeh et al. (2017d) the switching power of the structure is about 2 Kw/µm², while in Serajmohammadi et al. (2015) the authors used 1.5 Kw/µm² as the switching threshold of the resonant ring. In Daghooghi et al. (2018b) and Mehdizadeh et al. (2016), the authors combined several rings using waveguides to realize a 2 × 4 decoder, and the switching threshold of the resonant rings is about 2 Kw/µm² and 1 Kw/µm² respectively. In Daghooghi et al. (2018a), the basis of realization of the 2 × 4 decoder is the use of non-linear resonators, and the input intensity is 15 Kw/µm². Similarly, in Rostamizadeh et al. (2020), the authors use non-linear resonators to realize the final decoder with 2 inputs and 4 outputs and an input intensity equal to 15 Kw/µm². But in Mehdizadeh et al. (2017a) and Maleki et al. (2019), the authors used non-linear resonant cavities to realize a 2 × 4 decoder and the input intensity about 20 Kw/µm² and 10 Kw/µm² respectively.

The decoder proposed in this paper is composed of two parts, a combiner to mix the signals coming from the input and polarization ports, and a non-linear demultiplexer that acts as an optical switch. We used nonlinear and selective resonators to reduce the intensity applied to the decoder (Mehdizadeh et al. 2017a; Serajmohammadi et al. 2015; Daghooghi et al. 2018a). The dielectric used to realize the final structure is gallium arsenic GaAs proposed by Moungar et al. (2019) and Skauli et al. (2003), such that the linear refractive index is 3.37 around 1.55 (Moungar et al. 2019). We also used chalcogenide glass for the design of the resonators, with a linear index and a high non-linear Kerr coefficient equal respectively to 3.1 and 9 × 10⁻¹⁷ m²/w (Daghooghi et al. 2018a, b; Li 2010; Rostamizadeh et al. 2020; Delphi et al. 2019; Alipour-Banaei et al. 2014a, b; Farah et al. 2016; Badaoui et al. 2011; Chaker et al. 2020; Naghizade and Sattari-Esfahan 2020; Mehdizadeh et al. 2016; Mokhtari et al. 2020; Sharifi et al. 2017; Yan et al. 2019; Neisy et al. 2018; Rahmani and Mehdizadeh 2018; Mehdizadeh et al. 2016, 2017b, c, d; Moniem 2016; Gholamnejad and Zavvari 2017; Parandin et al. 2018; Fedaouche et al. 2018; Fedaouche 2016; Jiang et al. 2012; Ye et al. 2004; Assefa et al. 2004; Singh et al. 2017; Pal et al. 2017, 2018). The final structure of our decoder was simulated using COMSOL Multiphysics simulation software which is based on the FEM finite element method.

This paper is organized as follows: in the first section the non-linear resonator was presented. In the second section, we discussed the realization phase of our final structure which is composed of a combiner and an optical switch based on the ring resonators and in the third section we presented the simulation results and finally we ended with a conclusion.

2 Non-linear ring resonator

The realization of the ring resonator is a very important step for the realization of several optical devices. The resonator created is a 19 × 19 grating of the dielectric rods in the area, where the lattice constant is 610.54 nm and the radius is 128.29 nm with a refractive index
is about 3.37. The plane wave expansion (PWE) method is used to plot the band diagram under COMSOL Multiphysics software. The normalized frequency in terms of radius K-vector (Γ–X–M–Γ) (Moungr et al. 2019). According to the band diagram shown in Fig. 1, two photonic band gaps are obtained for TE mode, $0.34 < a/λ < 0.55$, where $1.11 \, \mu\text{m} < \lambda < 1.8 \, \mu\text{m}$ and $0.87 < a/λ < 0.92$ where $0.66 \, \mu\text{m} < \lambda < 0.70 \, \mu\text{m}$.

The non-linear resonator was obtained by removing a $4 \times 4$ array of the rods to create a resonant cavity, the latter was filled by 9 non-linear rods in the form of a circle creating a ring. The radius of these rods is the same as that of the fundamental structure and the dielectric used is chalcogenide glass with a linear refractive index equal to 3.1 and a non-linear Kerr coefficient equal to $9 \times 10^{-17} \, \text{m}^2/\text{w}$. This ring couples two waveguides, a BUS waveguide for the input and a DROP waveguide for the output. Figure 2 shows the non-linear resonator structure and Fig. 3 shows the resonator output spectrum.
3 Structure design

The proposed optical 2×4 decoder has a size of 45×29 of the dielectric rods in square array, it is composed of two stages: a combiner with two input ports A1, A2 and an excitation port E to excite our structure. The role of this device is to combine different intensities coming from different input ports. The second stage, is an optical switch with four output ports, it operates according to the amount of intensity applied to it, because the rods inside the resonators used in the realization of the switch are made of chalcogenide glass which has an index of refraction depending on the intensity, is known as the Kerr effect, and in general, $n = n_1 + n_2 I$ is defined for the Kerr effect where $n_1$ and $n_2$ are respectively the linear refractive index and the non-linear Kerr coefficient and I is the intensity of the light power (Daghooghi et al. 2018a, b; Li 2010; Rostamizadeh et al. 2020; Delphi et al. 2019; Alipour-Banaei et al. 2014a, b; Farah et al. 2016; Badaoui et al. 2011; Chaker et al. 2020; Naghizade and Sattar-Esfahlan 2020; Mehdizadeha et al. 2016; Mokhtari et al. 2020; Sharifi et al. 2017; Yan et al. 2019; Neisy et al. 2018; Rahmani and Mehdizadeh 2018; Mehdizadeh et al. 2016, 2017b, c, d; Moniem 2016; Gholamnejad and Zavvari 2017; Parandin et al. 2018; Fedaouche et al. 2018; Fedaouche 2016; Jiang et al. 2012; Ye et al. 2004; Assefa et al. 2004; Singh et al. 2017; Pal et al. 2017, 2018; Maleki et al. 2019; Mounkar et al. 2019; Skauli et al. 2003; Fibich and Gaeta 2000). So, one of these ports will be active and the others will be inactive, and we can change the state (active—inactive) of the ports by changing the amount of intensity applied to the switch. The final decoder structure can be seen in Fig. 4.

To create the first stage, i.e., the combiner, we have combined a divisor with an OR logic port by placing 3 rods of GaAs at the meeting point of the outputs of the OR logic port and the divisor such that their radius is “$R_p = 73.13 \text{ nm}$”, as shown in Fig. 5.

The logical port OR consists of two branches "input port A2 and excitation port E” having identical optical wavelengths to avoid phase difference between them at the point where the beams coming from these branches meet (Mehdizadeh et al. 2017d), and we placed 3 rods of GaAs of radius $R_p = 73.13 \text{ nm}$ at this point to guide the maximum part of the optical wavelengths to the output of the logical port. The OR logic port is shown in Fig. 5.

The role of power divider is very important for the proper functioning of the decoder, and to understand this importance, we imagine that our decoder works without a divider, we get two similar cases, that is to say in both cases we have the same

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Fig. 3 The output spectrum of the basic ring resonator
power that arrives at the input of the switch, and these two cases are: case 1 \((E = A_1 = 1\) and \(A_2 = 0\)), case 2 \((E = A_2 = 1\) and \(A_1 = 0\)) because the powers injected inside the ports are equal, and \(P = P_0 = 1\) Kw/µm². So with the use of a divider, we obtain two different power levels. In the case of: \((E = A_1 = 1\) and \(A_2 = 0\)), the divisor divides the power injected at port \(A_1\) by 2 \((P_0/2)\), and we get the half of power that will combine with the power that comes from logical port OR as shown in Fig. 5.

In the second stage, we realized a four-channel demultiplexer based on non-linear ring resonators which acts as an optical switch. The non-linear resonator was explained in the previous section (Sect. 2). The inner rod radius changes in each ring to specify the resonance wavelengths of this demultiplexer, the inner rod radii are: \(r_1 = 128.29\) nm, \(r_2 = 124\) nm, \(r_3 = 120\) nm, \(r_4 = 116\) nm corresponding respectively to the output ports \(O_1, O_2, O_3, O_4\). Figure 6 shows the proposed photonic crystal optical switch.
4 Simulation results

The proposed decoder was simulated using the 2D-FEM finite element method implemented in professional COMSOL Multiphysics software in TE mode. At the beginning we tested the correct operation of the demultiplexer (switch), so we excited the structure by an input optical signal at an intensity of 1 Kw/µm² (P₀), and we obtained four resonance wavelengths: 1550 nm, 1546.6 nm, 1543.2 nm, 1539.8 nm corresponding to the output ports O₁, O₂, O₃, O₄ respectively with transmission efficiencies equal respectively to 98.8%, 97.2%, 98%, 94.1%. Figure 7 illustrates the demultiplexer output spectra of the proposed photonic crystal optical switch presented in Fig. 6.

Fig. 6 The proposed photonic crystal optical switch

Fig. 7 The optical switch output spectra
Then we injected in the switch four optical signals have the same central wavelength is 1550 nm and different intensities are: 1 Kw/µm², 1.5 Kw/µm², 2 Kw/µm², 2.5 Kw/µm², and it is noticed that with each injected intensity, only one output port will be active such that the resonance wavelength is 1550 nm and the other ports will be inactive as shown in the Figs. 8, 9, 10 and 11.

Then we simulated the final structure of the proposed decoder, so we excited the input branches with the same intensity \(P_0 = 1\) Kw/µm² and a central wavelength equal to 1550 nm. First, we have all ports is inactive, i.e., no amount of signal reaches the switch, this is the state where the decoder is inactive. So, all output ports are inactive.

In the first case we have activated the excitation port E and ports \(A_1, A_2\) are inactive, so we have injected an intensity \(P_0\) inside E which will arrive at the switch, the resonator corresponding to \(O_1\) will couple the optical signal to the output port \(O_1\). Therefore, when E is active and \(A_1, A_2\) are inactive, port \(O_1\) will be active and is equal to 1. \(O_2, O_3, O_4\) will be inactive and will take the state 0, in this case, the normalized power at port \(O_1\) is 38%, at ports \(O_2, O_3, O_4\) are 2.5%, 1%, 0.9% respectively. And more generally the decoder is activated when E is activated without taking the other ports into consideration. In this case, the power levels for logic 0 and 1 are: 0.025 × \(P_0\) and 0.38 × \(P_0\) respectively, and the contrast ratio is 11.8 dB. We can calculate the contrast ratio values using the following formula:
CR = 10 \times \log\left(\frac{P_{on}}{P_{off}}\right), \text{ such that } P_{on} \text{ is the power value normalized to the logic 1 of the output ports, and } P_{off} \text{ is the power value normalized to the logic 0 of the output ports. This case can be seen in Fig. 12.}

In the second case, port E remains active, port A_2 is inactive and port A_1 is activated. The optical signal coming from port A_1 will be halved, and we get the half optical signal intensity \(0.5 \times P_0\) which will be combined with the optical intensity coming from port E, resulting in an overall intensity at the switch input equal to \(1.5 \times P_0\). In this case the resonant ring corresponding to O_2 will make the optical waves fall into the output waveguide O_2. So, when E, A_1 are active and A_2 is inactive, port O_2 will be ON and is 1, ports O_1, O_3, O_4 will be OFF and will take the state 0. The normalized power at O_2 is 39%, at O_1 5% and at O_3, O_4 equals 1%. So, the power levels for logics 0 and 1 in this case: 0.05 \times P_0 and 0.39 \times P_0. They result a contrast ratio equal to 8.9 dB. Figure 13 shows the results of this case.

In the third case, E is active, A_1 is inactive and A_2 is active, all the intensity injected into port A_2 (P_0) will be combined with the optical intensity coming from excitation port E, so that the overall intensity reaching the switch input is \(2 \times P_0\). In this case the resonator corresponding to port O_3 will guide the optical waves to the output O_3, such that the normalized power in this port is 37% and in O_1, O_2, O_4 are respectively equal to 0.8%, 0.4%,

Fig. 10 a Field distribution, b switch output spectra with an intensity of \(2 \times P_0\)

Fig. 11 a Field distribution, b switch output spectra with an intensity of \(2.5 \times P_0\)
2.1%. Consequently, when $E$, $A_2$ will be active and $A_1$ is inactive, $O_3$ will be ON and is equal to 1. $O_1$, $O_2$, $O_4$ will be OFF and take the state 0, as shown in Fig. 14. $0.021 \times P_0$ and $0.37 \times P_0$ are the power levels for logic 0 and 1 respectively, the contrast ratio is 12.45 dB.

In the last case, port $E$ is active and both input ports are active, the optical intensity that will arrive at the switch input level is $2.5 \times P_0$. The resonator that corresponds to $O_4$ will make the optical beam to the output port $O_4$ guide the optical beam to the output port $O_4$ and transforms its ON state. The figure illustrates the power levels of the output ports, and are 0.4%, 0.6%, 5%, 65% corresponding to $O_1$, $O_2$, $O_3$, $O_4$ respectively. When both input ports are active, $O_4$ will be ON and is 1, the other ports will be OFF and take the state 0, as shown in Fig. 15. The power levels for 0 and 1 are $0.05 \times P_0$ and $0.65 \times P_0$ respectively which results a contrast ratio of 11.13 dB.

And in general, to specify the logical state 0 of the global structure, we will take the highest power level for the logical state 0 of the simulation cases, and which is equal to $0.05 \times P_0$. And for the logical state 1 of the final structure, we will take the lowest power of the logical states 1 of the preceding cases, and equal to $0.37 \times P_0$. These levels give an important margin which can reduce the coupling problems with other devices. So, the contrast ratio of our structure is 8.6 dB.
Tables 1 and 2 summarize the proposed decoder operation cases.

It can be noticed in all cases where the decoder has activated a power drop because according to the Figs. 9, 10, 11 and 12. A small amount of power appears in the unwanted switch ports, and a large amount is lost in the combiner part at the divider and mixer before arriving at the switch input.

We can notice in Table 3 the characteristics of the structure, such that the maximum cross talk of ports $O_1$, $O_2$, $O_3$, $O_4$ is respectively $-16.25$ dB, $-15.9$ dB, $-16.77$ dB,
− 13 dB. The insertion losses for the output ports are respectively: − 2.07 dB, − 2.14 dB, − 2 dB, − 4.5 dB. The maximum cross talk can be calculated using the following formula: $10 \times \log \left( \frac{P_{low}}{P_{high}} \right)$, and insertion losses by: $10 \times \log \left( \frac{P_{in} - P_{out}}{P_{in}} \right)$ (Daghooghi et al. 2018b).

The ON–OFF values for $O_1$, $O_2$, $O_3$, $O_4$ are respectively: 11.8 dB, 8.9 dB, 12.45 dB, 11.13 dB. And the contrast ratio of the final structure is 8.6 dB.

The proposed structure is simple, less complex and with small size, based on a nonlinear demultiplexer to perform the switching operation, it is a different technique from the previous work. It works around the wavelength 1.55 µm, the third window of optical telecommunication. The decoder has good characteristics such as: the crosstalk values are low which proves the good switch operation, the contrast ratio values are high and the insertion loss is acceptable.

Table 4 shows the results obtained from our proposed structure in comparison with previous work. Therefore, we focus on some basic parameters of all-optical decoder design, such as: insertion loss for logic 0 and 1, crosstalk, contrast ratio, footprint, and power level. According to the table, the crosstalk value of our structure is low and lower than the value in Daghooghi et al. (2018b) and higher than the value obtained in Daghooghi et al. (2018a), but the value of crosstalk is not specified in Rostamizadeh et al. (2020), Askarian (2021) and Askarian and Akbarizadeh (2022). The power levels obtained in our work are significantly different between the edges compared to previous work, resulting in very good contrast, so its value compared to the results in Daghooghi et al. (2018b) and Askarian (2021) very high, and very close to from Daghooghi et al. (2018a), Rostamizadeh et al. (2020) and Askarian and Akbarizadeh (2022). Our decoder size is small and is equal to 487.07 µm², smaller than those proposed in Daghooghi et al. (2018a, b), Rostamizadeh et al. (2020) and Askarian and Akbarizadeh (2022) and slightly larger than those proposed in Askarian (2021). Compared to the results of Daghooghi et al. (2018a, b), the insertion loss of our work is high, but still acceptable. From the obtained results we can conclude that the proposed decoder $2 \times 4$ is improved in this study.
5 Conclusion

We have presented an efficient original architecture of all-optical $2 \times 4$ photonic crystal decoder based on non-linear ring resonators. The fundamental structure is composed of a non-linear demultiplexer with four output ports, functioning as a switch. And a three-input combiner to generate the different intensity levels to control the switch. The switch was realized using the nonlinear resonators. The switch output ports will be active from the intensities $P_0$, $1.5 \times P_0$, $2 \times P_0$, $2.5 \times P_0$. The proposed decoder has a size of $487.07 \ \mu m^2$ operates around 1.55 $\mu m$, the switching intensity of the structure is 1 Kw/$\mu m^2$. The maximum power levels for logic levels 0 and 1 are $0.05 \times P_0$ and $0.37 \times P_0$. The insertion loss is between $-2$ and $-4.5$ dB and the crosstalk is between $-15.9$ and $-22.1$ dB. The decoder has a good value of contrast ratio is equal to 8.6. The proposed structure has good characteristics for use in all-optical integrated communication circuits and systems.

Declarations

Conflict of interest All authors declare that they have no conflicts of interest to disclose. Due to the nature of this research, participants of this research did not agree for their data to be shared publicly, so supporting data is not available.

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