All optical analog to digital convertor using nonlinear photonic crystal ring resonators

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Abstract

In this paper an all optical analog to digital convertor was proposed based on photonic crystals. Four nonlinear ring resonators were used for designing a nonlinear demultiplexer, which can produce discrete levels of optical intensities from the input analog signal. Then by creating suitable connections between the output channels and waveguides of the demultiplexer, the coding section was created and the final structure was realized. For the proposed structure the maximum delay time is about 4 ps.

1 Introduction

Optical networks and systems are the best candidates for replacing electronic based networks in order to improve the processing speed and band width (Dutton 1998). We can use the benefits of an optical network, if we have a pure optical network in which all the building blocks such as waveguides (Mirjalili et al. 2020a, b; Mirjalili and Mirjalili 2015, 2016), filters (Dideban et al. 2017; Moloudian et al. 2016; Rashki and Seyyed Mahdavi Chabok 2016; Taalbi et al. 2013; Tavousi et al. 2017; Ying et al. 2015; Youcef Mahmoud et al. 2012), demultiplexers (Abolhaasani-Kaleibar and Andalib 2018; Fallahi et al. 2017; Kannaiyan et al. 2017, 2018; Talebzadeh et al. 2016a, b, 2017a, b; Venkatachalam et al. 2017), logic elements (Derakhshan et al. 2018; Hassangholizadeh-Kashtiban et al. 2019; Jandieri et al. 2018; Karimzadeh and Andalib 2018; Kumar et al. 2018; Ying et al. 2018; Zhang et al. 2019), adders (Andalib 2018; Jalali and Andalib 2019; Jiang et al. 2015a, b; Rahmani and Mehdizadeh 2017; Serajmohammadi et al. 2018; Vali-Nasab et al. 2019), subtractors (Askarian et al. 2019a, b; Moradi 2019; Parandin et al. 2017), comparators (Fakouri-Farid and Andalib 2018; Kaur 2013; Serajmohammadi et al. 2019; Surendar et al. 2019; Wang

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et al. 2007; Zhu et al. 2019), decoders (Alipour-Banaei et al. 2016; Khosravi and Zavvari 2018; Mehdizadeh et al. 2018; Moniem 2015; Salimzadeh and Alipour-Banaei 2018a, b), encoders (Gholamnejad and Zavvari 2017; Mehdizadeh et al. 2017a; Seif-Dargahi 2018), and multiplexer (Zhao et al. 2019) to be totally optical devices.

All of the aforementioned optical devices can be designed using photonic crystals (PhC) (Yablonovitch 1987). Photonic band gap (PBG) (Liu et al. 2015) feature of these structures help them in controlling the propagation of optical waves. Therefore it is possible to design any kind of optical devices with ultra-compact footprints. The other advantage of PhC based structure is that they do not need any non-optical biasing for the proper operation of the created structure.

Optical analog to digital convertors (ADCs) are one of the optical devices that can play crucial roles for realizing all optical data processing. In spite of their importance in optical systems, the number PhC-based optical ADCs are very limited. The first PhC-based Optical ADC was proposed using self-collimation effect (Miao et al. 2006). Another optical ADC was created using nonlinear resonant cavities (Youssefi et al. 2012). Cascading three optical power dividers was the other method that was used for designing optical ADC. The main problem of these works was that none of them can generate standard two bit binary codes. Mehdizadeh et al. (2017b, c, d) solved this problem and proposed optical ADCs which can generate standard 2-bit binary codes. Their proposed structures are composed of two main parts a nonlinear demultiplexer and an optical coder. At the coder stage they mostly used coupled waveguides for connecting three input ports into two output ports. This mechanism has large losses due to cross reflection between the coupled waveguides. Tavousi et al. (Tavousi et al. 2016; Tavousi and Mansouri-Birjandi 2017) discussed the design of optical 5-bit ADCs, using nonlinear ring resonators inside PhCs, but they do not presented any simulation results for analyzing the functionality of their proposed structures.

In this paper we are going to design and propose a novel optical ADC using PhC-based nonlinear ring resonators. The most significant goal of our work is to improve the efficiency of the coder stage of the proposed structure and reduce the optical loss.

2 Nonlinear demultiplexer

The first step in optical analog to digital conversion is to discretize the analog optical input signal. For this task we need a nonlinear optical demultiplexer. The nonlinear optical demultiplexer can be designed using four nonlinear ring resonators inside a two dimensional PhC structure. The basic two dimensional photonic crystal structure is composed of Si rods in air background. The radius and lattice constant of the Si rods are 119 nm and 595 nm respectively. It is well known that for designing a four channel optical demultiplexer we need to create an input waveguide, four output waveguides and four resonators that are located between the input waveguide and each output waveguide. As far as we know an optical ADC converts the continues analog input signal into discrete levels and then generates digital codes using these levels. For discretizing the analog optical signal based on its optical power we should use an optical structure which is sensitive upon the variation of optical power. Nonlinear PhCRRs can do this job, because of using nonlinear rods inside the ring, the resonant mode of the ring depends on the amount of optical power.

For creating the nonlinear ring resonators we used the idea proposed at (Zhu et al. 2019), in which some nonlinear rods made of doped glass were arranged around a 12-fold

quasi crystal shaped core. The radius of these nonlinear rods are the same as the basic structure, however their linear refractive index and Kerr coefficient are 1.4 and 10^{-14} m^2/W respectively. The radius core section rods for R1, R2, R3 and R4 are 119 nm, 107 nm, 97 nm and 97 nm respectively. R1-R4 rings should have different switching thresholds, in order to design these rings with different switching thresholds we should choose different values for R1-R4. The nonlinear demultiplexer is shown in Fig. 1.

The optical behavior of the nonlinear demultiplexer for different values of input optical signal are shown in Fig. 2. When the input intensity is less than 1 W/μm^2, none of the resonators can drop the optical waves therefore for this optical intensity all the output ports will be OFF. When the optical intensity of the input signal is between 1 and 2 W/μm^2, R1 can drop the optical waves into its corresponding output waveguide. Therefore in this case only Ch1 can be ON. When the optical intensity of the input signal is between 2 and 3 W/μm^2, R2 can drop the optical waves into its corresponding output waveguide. Therefore in this case only Ch2 can be ON. Finally when the optical intensity of the input signal is between 3 and 4 W/μm^2, both R3 and R4 can drop the optical waves into their corresponding output waveguides. Therefore in this case both Ch3 and Ch4 can be ON.

3 Optical ADC

As shown by designing a nonlinear demultiplexer we successfully discretized the analog input signal into four levels. Now in this step we should convert these levels into 2-bit standard binary codes. For this purpose we should perform some modifications inside the proposed nonlinear demultiplexer. In order to create the first output port of the proposed ADC we connected Ch1 and Ch3 together using an optical waveguide. Then this waveguide was coupled into the first output port using two extra nonlinear ring resonators named R5 and R6. The R5 and R6 resonators are as the same as the R1 and R3 respectively. Similarly In order to create the second output port of the proposed ADC we connected Ch2 and Ch4 together using an optical waveguide. Then this waveguide was coupled into the second output port using two extra nonlinear ring resonators named R7 and
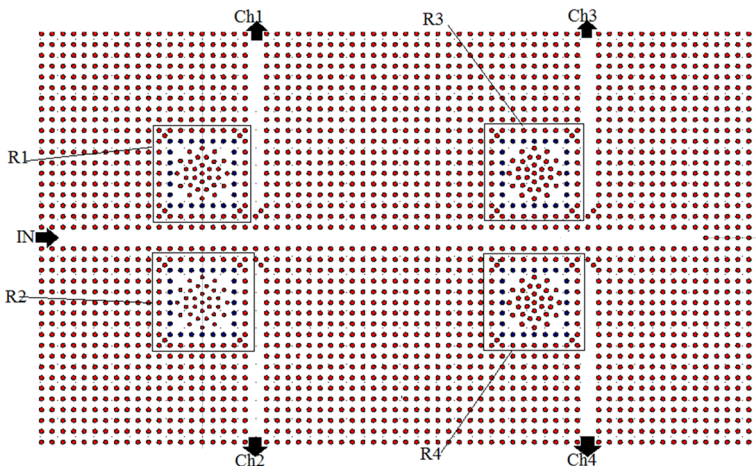
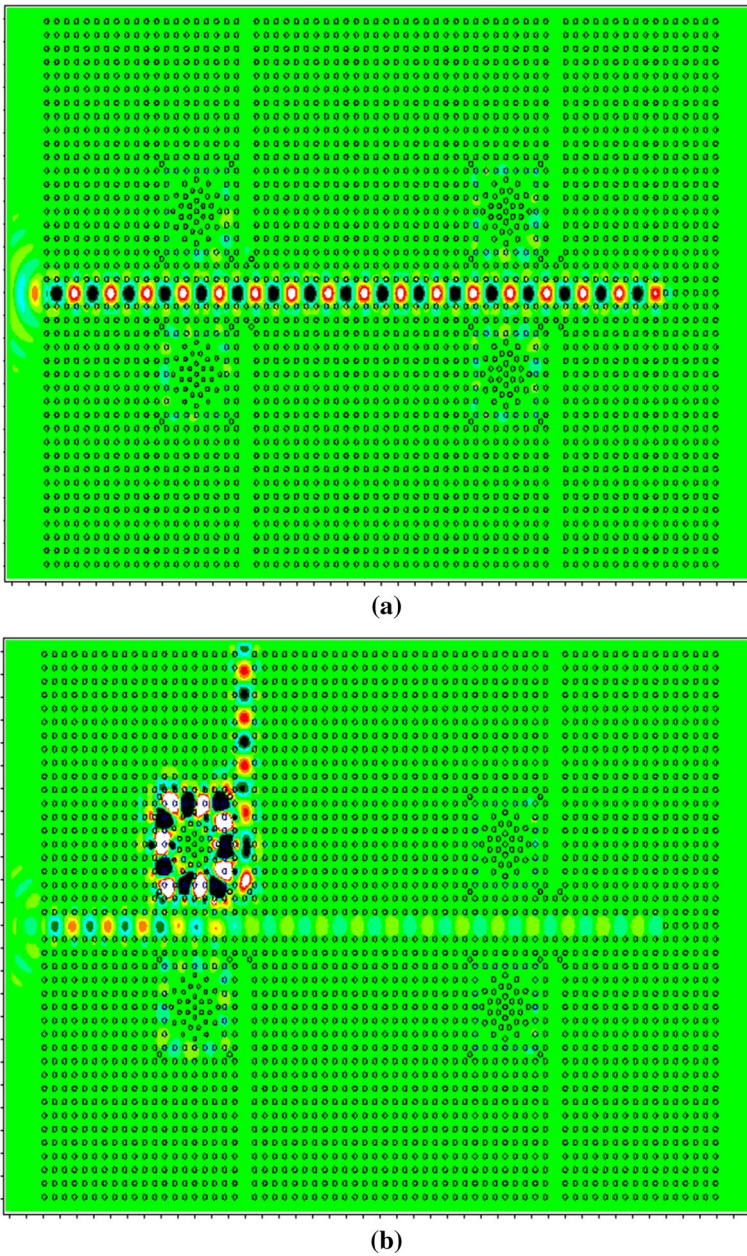**Fig. 1** The nonlinear demultiplexer

(a)

(b)

Fig. 2 The optical behavior of the nonlinear demultiplexer

R8. The R5 and R6 resonators are as the same as the R2 and R4 respectively. The final structure is shown in Fig. 3.

The optical behavior of the proposed structure for different values of optical intensity of the input signal are shown in Fig. 4. As discussed when the optical intensity of
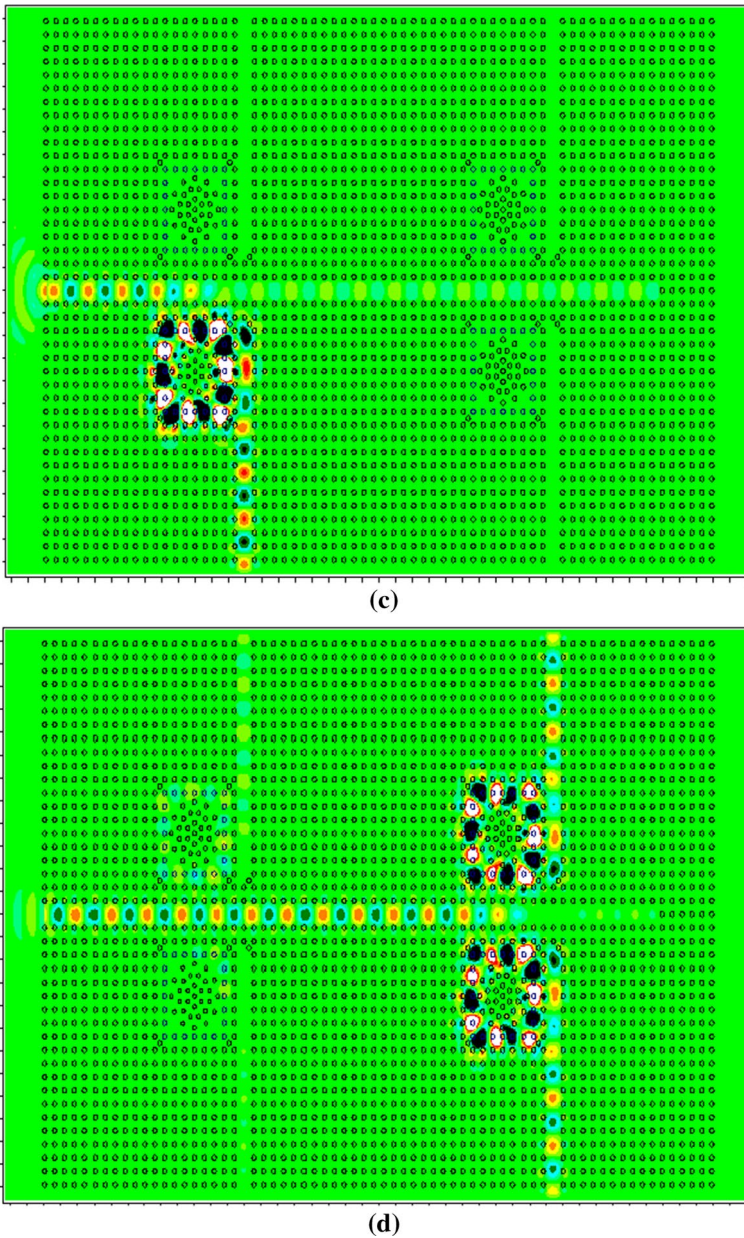
(c)

(d)

Fig. 2 (continued)

the input signal is less than 1 W/μm², none of the resonators can drop the optical waves into their adjacent waveguide as a result in this case both output ports will be OFF and the generated code will be 00. When the optical intensity of the input signal varies between 1 and 2 W/μm², R1 can drop the optical waves into its adjacent waveguide. These waves travel toward R5 and R6. Because R5 is the same as the R1, therefore
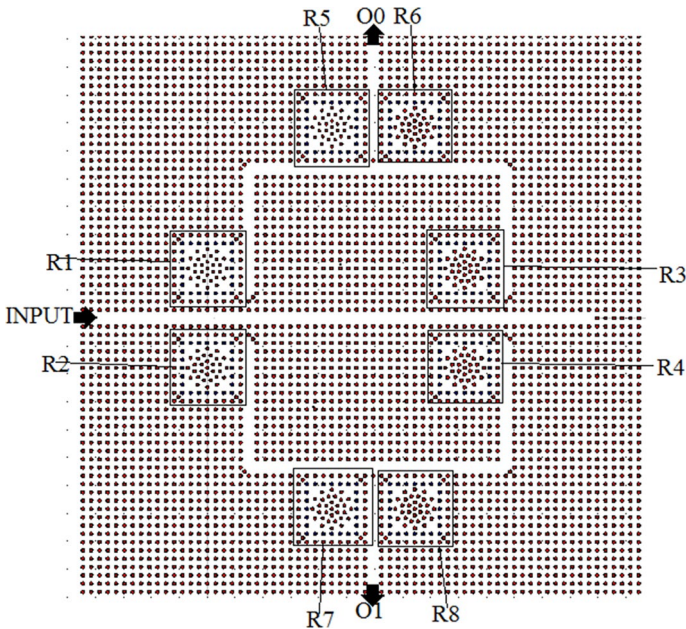
Fig. 3 The proposed optical ADC

it can drop these waves into the first output waveguide and turn on O0. As a result in this case O0 is ON, but O1 is OFF, and the ADC can generate 01 code at the output ports. When the optical intensity of the input signal varies between 2 and 3 W/μm², R2 can drop the optical waves into its adjacent waveguide. These waves travel toward R7 and R8. Because R7 is the same as the R3, therefore it can drop these waves into the second output waveguide and turn on O1. As a result in this case O1 is ON, but O0 is OFF, and the ADC can generate 10 code at the output ports. Finally when the optical intensity of the input signal varies between 3 and 4 W/μm², R3 and R4 can drop the optical waves into their adjacent waveguides. Also R6 and R8 can guide these waves toward the output ports. As a result in this both output ports will be ON, and the ADC can generate 11 code at the output ports.

The output diagrams of the proposed structure are shown in Fig. 5. When the optical intensity of the input signal is less than 1 W/μm², the amount of normalized output intensity at the output ports are less than 1%. For the input intensity being between 1 and 2 W/μm², the normalized optical intensity at O0 and O1 are 91% and 1% respectively. Also the delay time for O0 is about 4 ps. When the input intensity varies between 2 and 3 W/μm², the normalized optical intensity at O0 and O1 are 1% and 95% respectively. Also the delay time for O1 is about 4 ps. Finally when the input intensity varies between 3 and 4 W/μm², the normalized optical intensity at O0 and O1 are 45% and 45% respectively. Also the delay time for O0 and O1 are about 4 ps. The different working states of the proposed structure are summarized at Table 1. The proposed structure has better delay times compare with previous works (Mehdizadeh et al. 2017b, 2017c, 2017d).
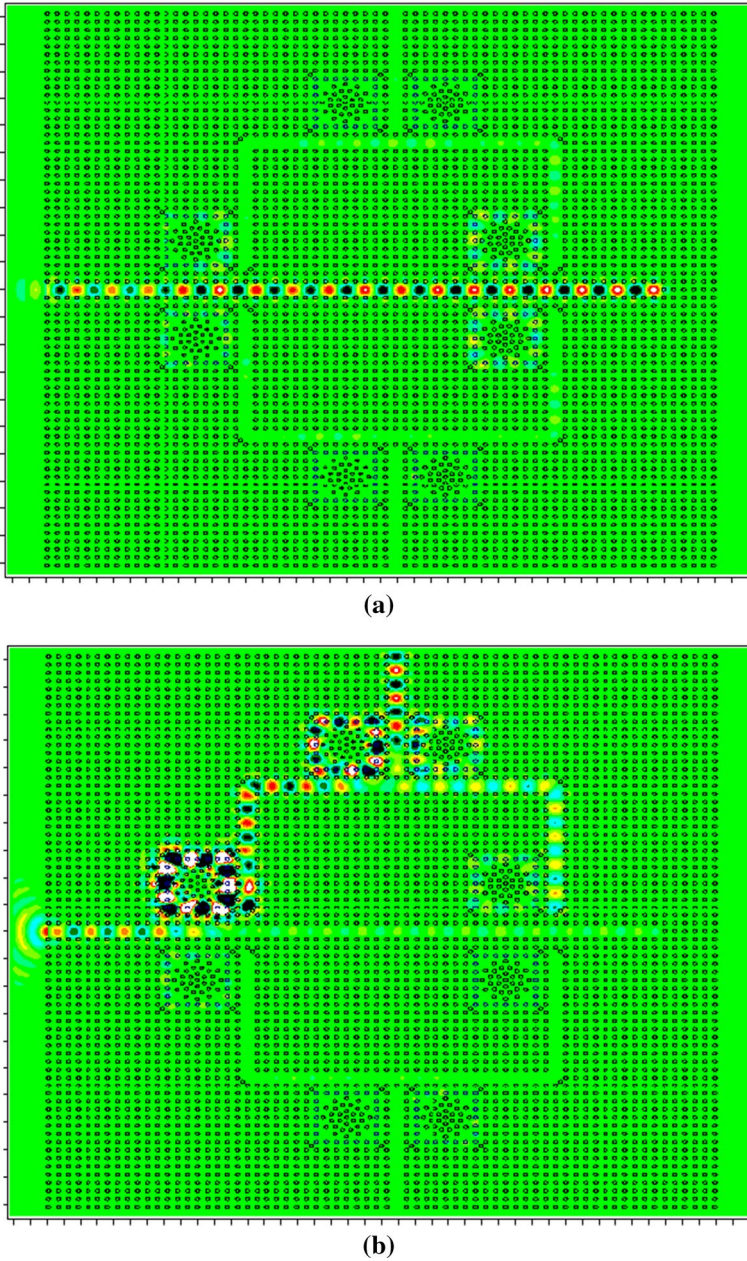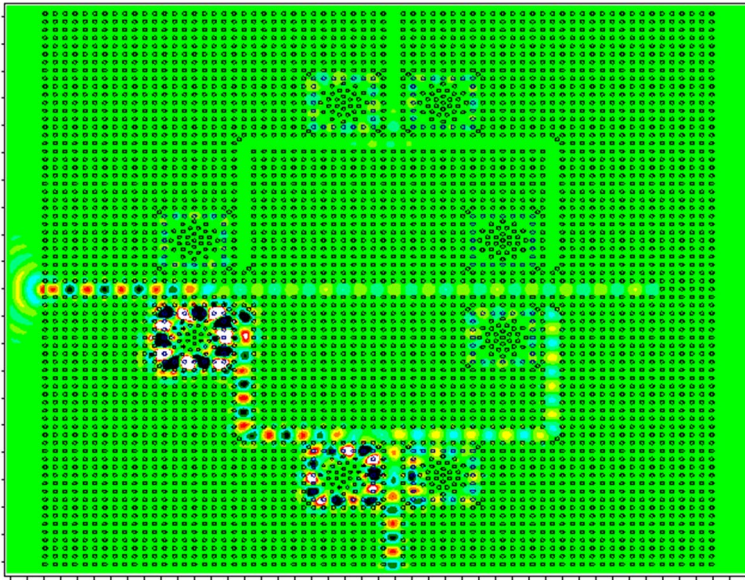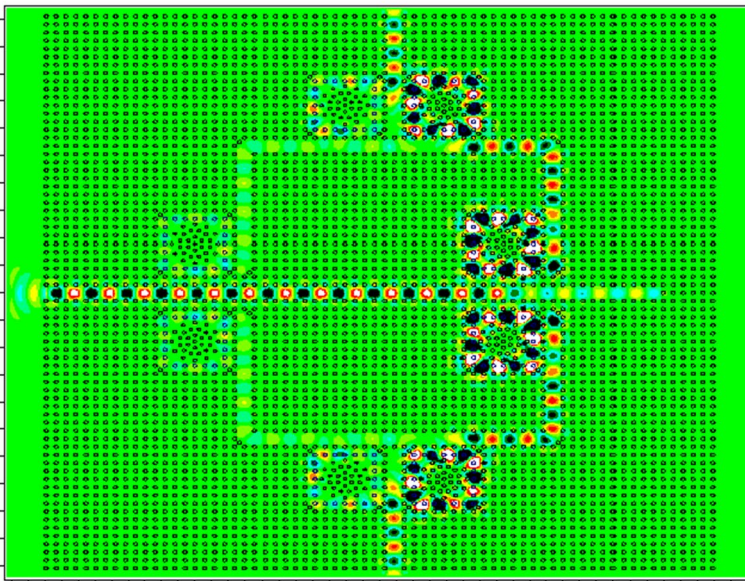
(a)

(b)

Fig. 4 The optical behavior of the proposed ADC

(c)

(d)

Fig. 4 (continued)

(a)

(b)
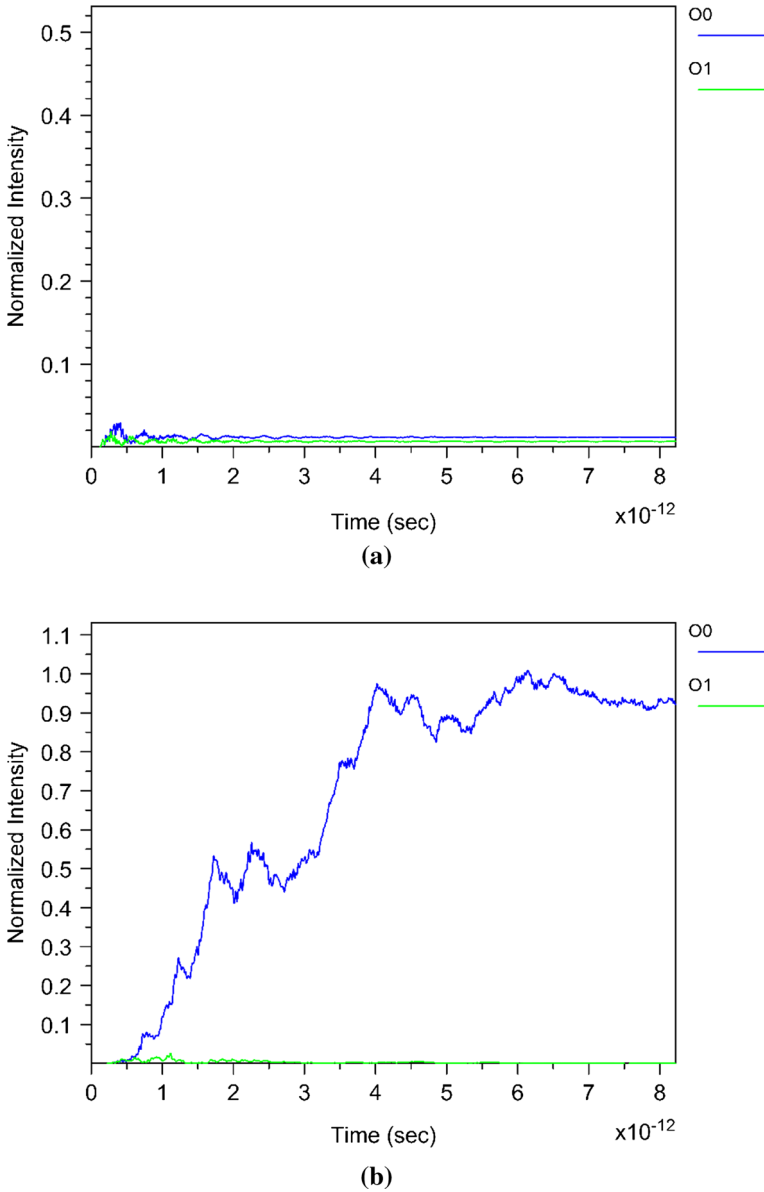
Fig. 5 The time response diagrams for the proposed ADC

(c)

(d)
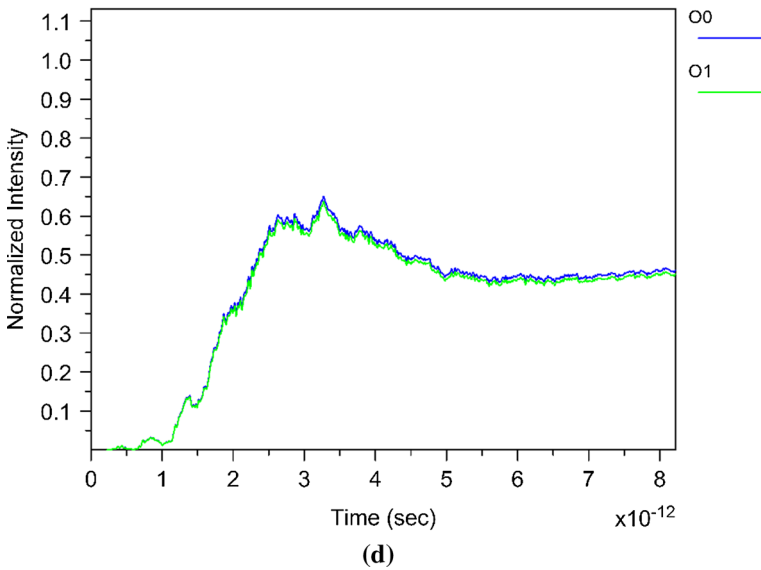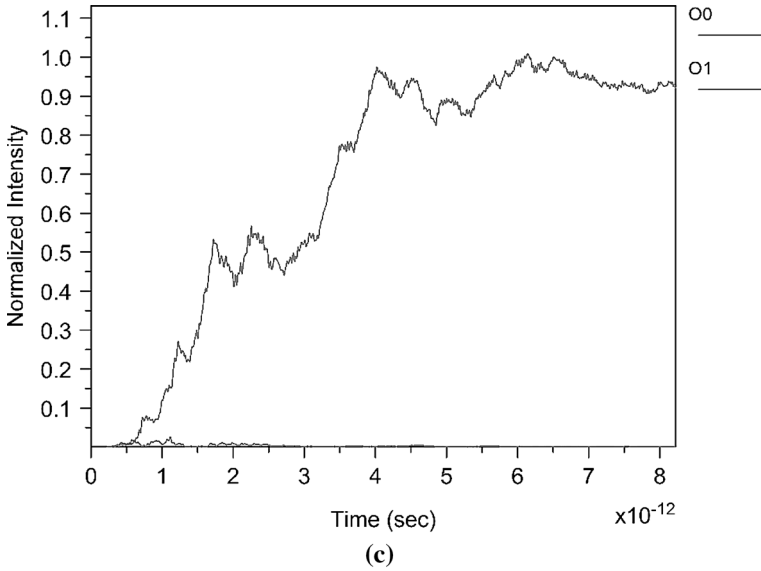
Fig. 5 (continued)

Table 1 Working states of the proposed ADC

Pin (W/μm^2)	O1	O0
$0 < P_{in} < 1$	0	0
$1 < P_{in} < 2$	0	1
$2 < P_{in} < 3$	1	0
$3 < P_{in} < 4$	1	1

4 Conclusion

An all optical nonlinear demultiplexer was designed using four nonlinear ring resonators. The nonlinear demultiplexer can convert the analog input signal into discrete levels of optical intensities. Then the final structure was created by providing suitable connections between the output waveguides of the nonlinear demultiplexer. The simulations prove that the proposed structure can generate four 2 bit codes from the input analog signal. The maximum delay time of the ADC is about 4 ps.

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