# Performance analysis of dual leaf shaped PC based optical encoder

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In this paper, a dual leaf shaped 4*2 optical encoder is proposed and designed in triangular lattice using Two Dimensional Photonic Crystal (2DPC). The dual leaf shaped ring resonator along with line defects and cavities are introduced in this proposed structure. Plane Wave Expansion method (PWE) is implemented to define the band gap of the proposed structure. The function of the structure is simulated by using 2D Finite Difference Time Domain Method (2D-FDTD). The proposed encoder size is 17.6μm x 15.2μm =267.52 $\mu m^2$. The proposed encoder is suitable for high speed applications such as integrated circuits and devices.

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*Keywords*: Photonic crystal, Encoder, Dual leaf shaped resonator, FDTD, Triangular lattice

## 1. Introduction

A vast growth of optical communication and optical networking technologies leads to a wide range of various high speed applications such as optical computing, neuromorphic computing, microwave computing and quantum computing etc. [1]. Since, it requires optical components and devices for transmitting, processing and receiving large scale of data in order to achieve high speed terahertz communication. Currently, most of the researchers focus on designing the Photonic Crystal (PC) based devices due to its exclusive properties of guiding the light of exacting wavelength inside the PC [2]. Compactness, high speed, and low power consumption are the exceptional qualities of PC [3]. The Photonic Band Gap (PBG) is the significant properties of the PC and breaking of its periodicity property by creating defects in the PC structure. Hence light propagation along the PC which is suitable for various high speed optical networks and communication link [4]. PC are classified into three types, namely, 1D, 2D and 3D. Among this 2D PC based structure are most utilized platform to design the various photonic devices such as logic gates [5-7], multiplexer [8,9] and demultiplexer [10], filters [11], sensor [12] and etc.

The optical encoders play a vital role in communication system such as telecommunication and networking. It can reduce the $2^N$ inputs to N-bit binary by utilizing the binary logic '0' and logic '1'. Only one input is activated at a time and other outputs are turned OFF. The compressed digital data transmission process is achieved by using such optical encoder and is also fit for analog to digital conversion [13].

In the literature survey, PC based optical encoder is devised using square and triangular lattice using defects and ring resonators. S. Naghizade was devised an optical 4*2 encoder using OR gates using low input power and offers high power efficiency [14]. S. Monisha et al. reported a reversible optical encoder by using multi-hexagonal shaped arrangement paralleled in the structure. The contrast ratio of the structure is obtained around 12.18dB [15]. Chongu Zang was proposed an optical coherent encoder/decoder by implementing the phase shifter [16]. The combination of optical splitter and four port switch were implemented in encoder design by Farhad Mehdizadeh et al. The structure had the switching speed of 2GHz and operated at about 20W/$\mu m^2$ [17]. Fatemeh haddadan and Mohammad Soroosh was designed the all-optical 8*3 encoder without using the resonator and maximum delay time as 5ps [18]. In this literature, self-collimation effect is used for designing the optical encoder. The optical encoder is realized by using mirrors and beam splitter and determined the response period of such structure [19]. In addition, the 4*2 encoder is designed using cavity and linear/nonlinear ring resonator [20-24] with different materials.

In this work, an optical encoder is designed by means of dual leaf shaped 2DPC structure in order to enhance the transmission efficiency. The guided mode of propagation and PBG are determined using the PWE method. The proposed PC structure has four input waveguides and two output waveguides which are coupled through the resonator. The transmission behavior of the proposed encoder is analyzed using 2D FDTD method. It works in the second optical window and it is fit for all optical integrated and computing devices and systems.

The rest of the paper is structured as follows: Section 2 describes the design of 4*2 optical encoder. Section 3 defines the simulation results and discussion of proposed encoder. Sections 4 conclude the proposed work.

## 2. Design of 4*2 encoder

The proposed 4*2 encoder is designed using an array of 27*27 in triangular lattice along X and Z direction. It is constructed by using six waveguides. The proposed design 4*2 encoder is shown in Fig. 1. And its truth table is shown in Table 1.

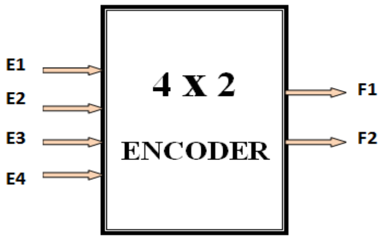



*Fig. 1. Block diagram of optical 4*2 encoder*

*Table 1. Truth Table for 4*2 optical encoder*

| S. No. | Input | | | | Output | |
|---|---|---|---|---|---|---|
| | E1 | E2 | E3 | E4 | F1 | F2 |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 1 | 0 | 0 | 0 | 1 |
| 3 | 0 | 0 | 1 | 0 | 1 | 0 |
| 4 | 0 | 0 | 0 | 1 | 1 | 1 |

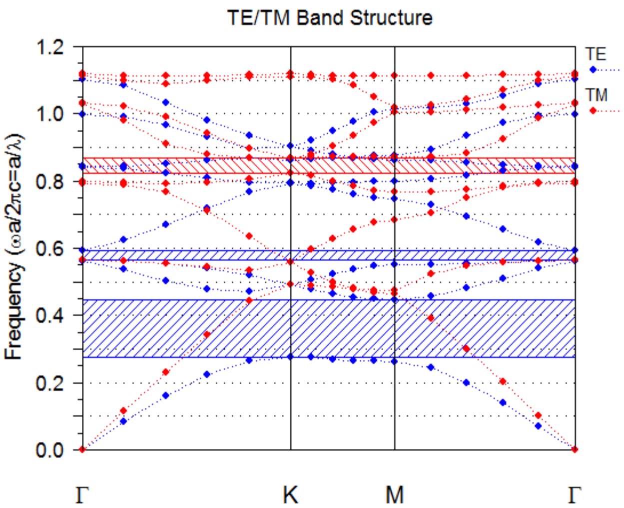



*Fig. 2. Band diagram of proposed 4*2 encoder (color online)*

The band diagram of the proposed encoder is depicted in Fig. 2. It has two TE PBG and TM PBG where first TE PBG is considered. The wavelength range of TE PBG is ranging from 0.27a/λ to 0.44 a/λ with the wavelength range from 1477 nm to 2368 nm.

The schematic design of proposed 4*2 encoder is shown in Fig. 3. The 4*2 encoder is constructed by six waveguides where four waveguides are considered as input ports of the encoder namely E1, E2, E3 and E4 and two waveguides are connected to the upper and lower leaf shaped resonator and it is considered as the output ports namely F1 and F2. The silica material is used for this structure which has the refractive index of 3.46 and the entire structure has the radius of 130 nm. The lattice constant is denoted as 'a' which is equal to 650 nm. The outer radius R and inner radius r are optimized to 45 nm and 55 nm which are positioned on the upper and lower part of the dual leaf shaped resonator. The reflection of the optical signal is eliminated by varying the refractive index of the material.

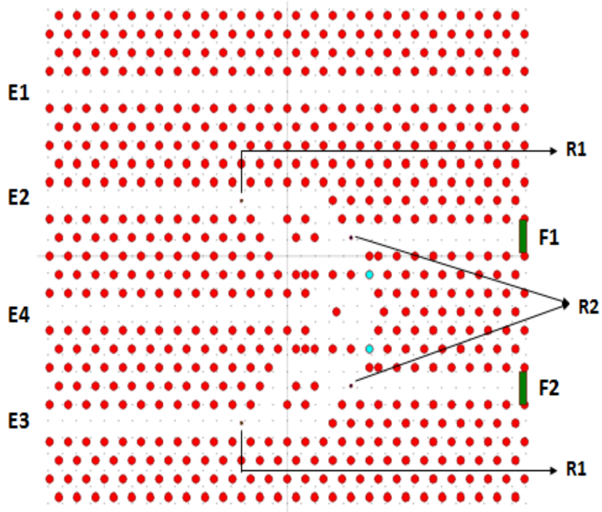



*Fig. 3. Schematic structure of optical 4*2encoder (color online)*

## 3. Results and discussion

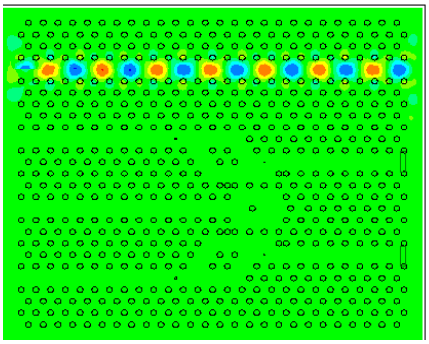
The functional performance of the 4*2 encoder is simulated and evaluated its different input stages. The field distribution of 4*2 encoder is depicted in the Fig. 4.

**Case 1:**
When E1 is ON, the optical signal enters into the waveguide E1and does not reach at the E2, E3 and E4 respectively. The normalized output power at F1 and F2 is almost zero.

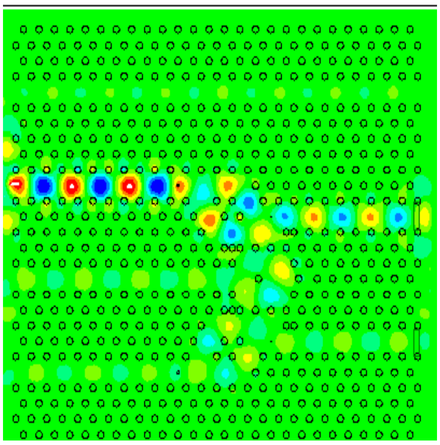
**Case 2:**
When E2 is ON, the optical waves pass through it and enter into the upper part of the leaf like resonator and reaches the output port F1=1, and F2=0. The output power at F1and F2 is 96% and 8%, respectively.

**Case 3:**
When E3 is ON, the optical waves go through the waveguide and reaches the lower part of leaf shaped resonator and drawn across the rods to reach the output where 9% at F1 and 100% at F2.

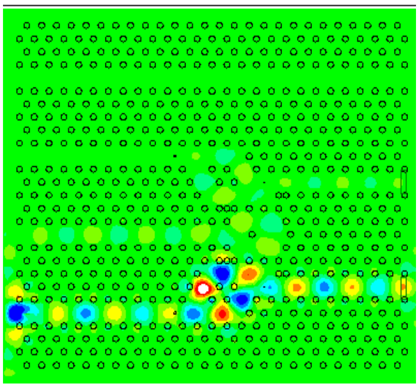
**Case 4:**
When E4 is ON, the optical signal dropped in to dual leaf shaped resonator and receive on the output ports and hence both the F1 and F2 become ON. The normalized output power at output ports F1 and F2 is around 88%.



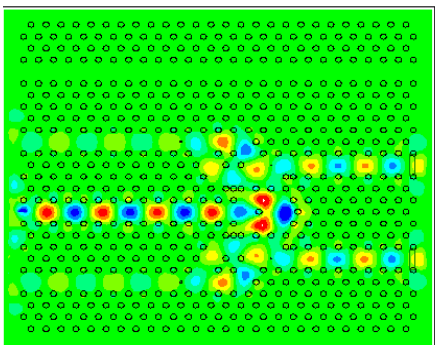
(a) E1=1, E2=E3=E4=0, F1=0, F2=0



(b) E2=0, E1=E3=E4=1, F1=1, F2=0

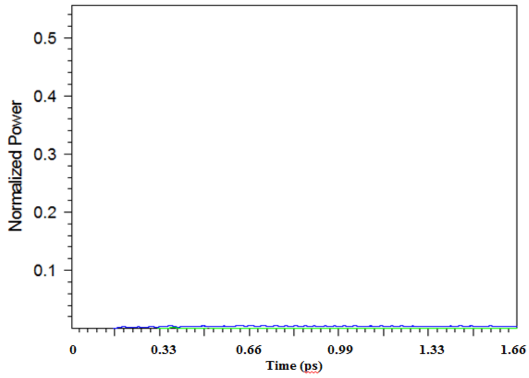


(c) E3=1, E1=E2=E4=0, F1=1, F2=0

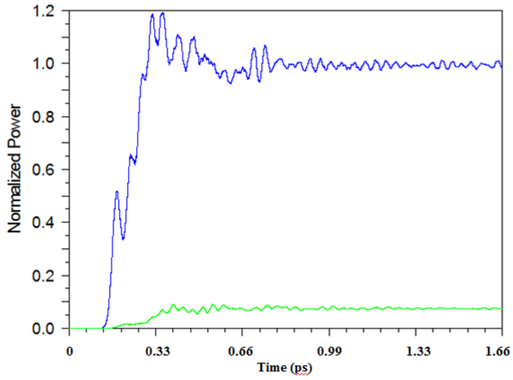


(d) E4=1, E1=E2=E3=0, F1=1, F2=1

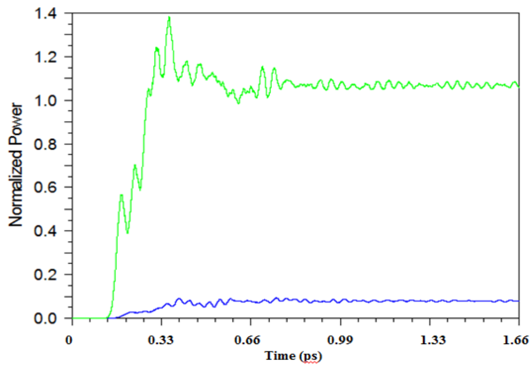
*Fig. 4. Optical field distribution of proposed encoder at (a) E1=1, E2=E3=E4=0, F1=0, F2=0, (b) E2=1, E1=E3=E4=0, F1=0, F2=1, (c) E3=1, E1=E2=E4=0, F1=1, F2=0 and (d) E4=1, E1=E2=E3=0, F1=1, F2=1 (color online)*



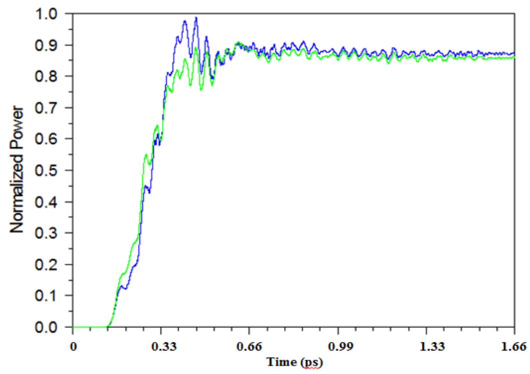

(a) E1=1, E2=E3=E4=0, F1=0, F2=0




(b) E2=1, E1=E3=E4=0, F1=0, F2=1




(c) E3=1, E1=E2=E4=0, F1=1, F2=0




(d) E4=1, E1=E2=E3=0, F1=1, F2=1

*Fig. 5. Output response of the proposed encoder at (a) E1=1, E2=E3=E4=0, F1=0, F2=0,(b) E2=1, E1=A3=E4=0, F1=0, F2=1,(c) E3=1, E1=E2=E4=0, F1=1, F2=0 and (d) E4=1, E1=E2=E3=0, E1=1, E2=1 (color online)*

Fig. 5 shows the output performance of the 4*2 encoder and describes its functional performance. Table 2 represents the normalized output transmission of the proposed encoder.

*Table 2. Output performance of 4*2 optical encoder*

| S. No. | Input | | | | Output % | | **Response Time** | **Bit rate** | **Contrast Ratio** |
|---|---|---|---|---|---|---|---|---|---|
| | E1 | E2 | E3 | E4 | F1 | F2 | | | |
| 1 | 1 | 0 | 0 | 0 | 2 | 0 | 1.464ps | 0.68Tbs | -20.7dB |
| 2 | 0 | 1 | 0 | 0 | 96 | 8 | | | |
| 3 | 0 | 0 | 1 | 0 | 4 | 100 | | | |
| 4 | 0 | 0 | 0 | 1 | 89 | 88 | | | |

The contrast ratio of 4*2 encoder is 13.97 dB, which is obtained by Power level at logic 0 is approximately 0.4 (4%) and the power level of logic 1 is 1 (100%) using the following formula.

$$CR=10 \log (P_1/P_0) \text{ dB}$$

The output performance of the proposed optical encoder is listed in Table 2. It is observed that the response period, bit rate and contrast ratio of the proposed optical encoder is 1.464 ps, 0.68T bps and -20.7 dB, respectively. The aforementioned parameters are sufficient for real time applications, hence, it can support for telecommunication devices.

*Table 3. Impact of output power and contrast ratio for different inner rod radius*

| S.NO | Inner rod radius (nm) | Outer rod radius (nm) | Output Power | | Contrast Ratio (dB) |
|---|---|---|---|---|---|
| | | | Logic 0 | Logic 1 | |
| 1 | 25 | 55 | 16 | 82 | 7.09 |
| 2 | 30 | 55 | 11 | 87 | 8.98 |
| 3 | 35 | 55 | 7 | 94 | 11.28 |
| 4 | 40 | 55 | 6 | 98 | 12.13 |
| 5 | 45 | 55 | 4 | 100 | 13.97 |
| 6 | 50 | 55 | 7 | 90 | 11.09 |
| 7 | 55 | 55 | 11 | 85 | 8.88 |
| 8 | 60 | 55 | 14 | 82 | 7.69 |
| 9 | 65 | 55 | 17 | 79 | 6.67 |
| 10 | 130 | 130 | 23 | 72 | 4.95 |

The impact of output power variation and contrast ratio while varying the inner rod radius are listed in Table 3. From the table, it is noticed that the output power and contrast ratio is better when the inner rod radius at 45 nm than other radius. Similarly, the impact of output power variation and contrast ratio while varying the outer rod radius is reported in Table 4. From the table, it is noticed that the output power and contrast ratio is better when the outer rod radius at 55 nm than other radius. Hence, in this attempt, the inner and outer rod radii are kept as 45 nm and 55nm, respectively.

*Table 4. Impact of output power and contrast ratio for different outer rod radius*

| S.NO | Inner rod radius (nm) | Outer rod radius (nm) | Output Power | | Contrast Ratio (dB) |
|---|---|---|---|---|---|
| | | | Logic 0 | Logic 1 | |
| 1 | 45 | 35 | 13 | 87 | 8.25 |
| 2 | 45 | 40 | 11 | 90 | 9.12 |
| 3 | 45 | 45 | 9 | 94 | 10.18 |
| 4 | 45 | 50 | 6 | 97 | 12.08 |
| 5 | 45 | 55 | 4 | 100 | 13.97 |
| 6 | 45 | 60 | 5 | 98 | 12.92 |
| 7 | 45 | 65 | 7 | 96 | 11.37 |
| 8 | 45 | 70 | 10 | 94 | 9.73 |
| 9 | 45 | 75 | 11 | 90 | 9.12 |
| 10 | 130 | 130 | 23 | 72 | 4.95 |

*Table 5. Comparison of functional parameters in proposed encoder designs*

| Ref. | Encoder Type | Lattice | Defects | Footprint $\mu m^2$ | Contrast Ratio (dB) | Response Time (ps) |
|---|---|---|---|---|---|---|
| [14] | 4*2 | Square | Line and Point defects | 625 | 15 | 0.7 |
| [15] | 4*2 | Square | Ring resonator | *** | 11.5 | *** |
| [17] | 4*2 | Square | Line and Point defects | 880 | 7.324 | 0.2 |
| [19] | 4*2 | Hexagonal | Line and Point defects | 3795 | 7.84 | 1.4 |
| [23] | 4*2 | Square | Line and Point defects | 880 | *** | 2 |
| [25] | 4*2 | Square | Ring resonator | *** | *** | 2 |
| [26] | 4*2 | Square | Ring resonator | *** | 9.2 | 1.8 |
| [27] | 4*2 | Square | Ring resonator | 128 | 7.11 | 0.1 |
| [28] | 4*2 | Hexagonal | Ring resonator | 1927 | *** | 1 |
| [29] | 4*2 | Square | Ring resonator | 1225 | *** | 1.9 |
| [30] | 4*2 | Square | Ring resonator | 240.5 | 9.54 | *** |
| [31] | 4*2 | Square | Ring resonator | 795.6 | 9.5 | 1.8 |
| Proposed work | 4*2 | Hexagonal | Ring resonator | 267.52 | 13.97 | 1.464 |

*** Not mentioned

The functional parameters of the proposed encoder such as footprint, contrast ratio and response time are compared with the reported encoder as listed in Table 5. From the table it is envisioned that if contrast ratio is increased, the response time is decreased. IF both contrast ratio and response time are good, the size of the device is larger. However, the proposed encoder offered better contrast ratio, high bit rate and quick response time that reported encoder. Hence, these structures can be used for high speed computing photonic integrate circuits.

## 4. Conclusion

The 4*2 encoder is designed and investigated using dual leaf shaped resonator along with line defects. The optical behavior of such encoder is simulated and analyzed using the FDTD method. The ON state is above 90% and OFF state is below 1%. The response time and bit rate of the proposed encoder is 1.464 ps and 0.68 Tbps, respectively. The smart structure and fast response are the merits of proposed structure and it is appropriate for all high speed optical integrated circuits.

## References

[1] Peipeng Xu, Jiajiu Zheng, ACS Photonics **6**(2), 553 (2019).
[2] Wen-PiaLin, Yu-Fan Hsu, Han-Laung Kuo, Journal of Modern Physics **2**(3), 144 (2014).
[3] D. R. Solli, J. M. Hickmann, Optical Materials **33**(3), 523 (2011).
[4] J. D. Joannopoulos et al., Photonic Crystal: Modeling of Flow of Light, Princeton University Press, Princeton, New Jersey, 2008.
[5] Enaul Haq Shaik, Nakkeeran Rangaswamy, Journal of Computational Electronics **17**(1), 337 (2018).
[6] Jayson K. Jayabarathan, G. Subhalakshmi, S. Robinson, Journal of Optical Communication **39**(2), 1 (2018).
[7] Enaul Haq Shaik, Nakkeeran Rangaswamy, Journal of Computational Electronics **17**(1), 337 (2018).

[8] Y. Wang, H. Lv, T. Jiang, K. Zhang, Optik **192**, 162878 (2019).
[9] M. Zavvari, Journal of Optical Communications **40**(2), 135 (2019).
[10] R. Rajasekar, S. Robinson, Journal of Nanoelectronics and Optoelectronics **14**(6), 753 (2019).
[11] R. Rajasekar, S. Robinson, Optical Materials **85**, 474 (2018).
[12] J. K. Jayabarathan, G. Subhalakshmi, Journal of Ovonic Research **14**(5), 351 (2018).
[13] R. Massoudi, M. Najjar, F. Mehdizadeh, Optical and Quantum Electronics **51**(87), 1 (2019).
[14] S. Naghizade, H. Khoshsima, Journal of Optical Communications **39**, 1 (2018).
[15] S. Monisha, D. Saranya, A. Rajesh, Optical and Quantum Electronics **51**(6), 1 (2018).
[16] Chongfu Zhang, Kun Qiu, Optics and Laser in Engineering **46**(8), 582 (2008).
[17] Farhad Mehdizadeh, Hamed Alipour-Banaei, Somaye Serajmohammadi, Journal of Modern Optics **64**(13), 1233 (2017).
[18] F. Haddadan, M. Soroosh, Photonic Network Communications **37**, 83 (2019).
[19] Hamed Alipour-Banaei, Mehdi Ghorbanzadeh Rabati, Parisa Abdolaahzedeh-Badelbou, Farhad Mehdizadeh, Physica E: Low-dimensioal Systems and Nanostructures **75**, 77 (2016).
[20] Mohsen Makvandi, Mohammad Javad Maleki, Mohammad Soroosh, Journal of Applied Research in Electrical Engineering **27**, 6 (2020).
[21] S. Rajaseker, G. Thavasi Raja, S. Robinson, Photonic Network Communications **40**, 31 (2020).
[22] Fatemeh Haddadan, Mohammad Soroosh, Navid Alaei-Sheini, Applied Optics **59**(7), 2179 (2020).
[23] Fatemeh Hadadan, Mohammad Soroosh, International Journal of Optics and Photonics **13**(2), 119 (2019).
[24] Farhad Mehdizadeh, Mohammad Soroosh, Hamed Alipour-Banaei, IET Optoelectronics **11**(1), 29 (2017).
[25] Amir Salimzadeh, Hamed Alipour-Banaei, Journal of Optical Communications **410**, 793 (2018).
[26] Hamed Seif-Dargahi, Photonic Network Communications **36**(2), 272 (2018).
[27] Tamer S. Mostafa, Nazmi A. Mohammed, El-Sayed M. El-Rabaie, Journal of Computational Electronics **17**(1), 1, (2018).
[28] S. Gholamnejad, M. Zavvari, Optical Quantum Electronics **49**, 302 (2017).
[29] T. A. Moniem, Journal of Modern Optics **63**(8), 735 (2015).
[30] O. Iman, N. Rafah, Optik- International Journal of Light Electron Optics **127**(19), 7835 (2016).
[31] H. Seif-Dargahi, Photonics Network Communications **36**(2), 272 (2018).

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