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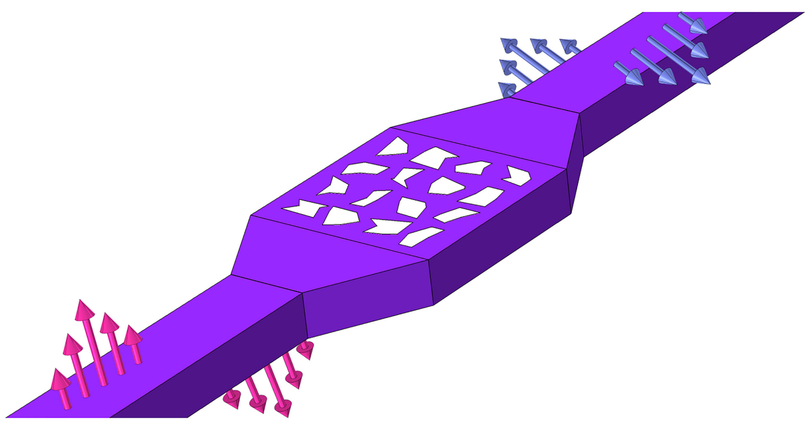

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On-Chip Ultra-Small Arbitrary-Elliptical-Polarization Converters

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Abstract: On-chip arbitrary-elliptical-polarization converter plays a key role in optical information processing. However, the traditional method of manually adjusting parameters for designing devices is limited in function. In this letter, on-chip ultra-small arbitrary-elliptical-polarization converters are realized through optimization algorithms based on genetic algorithm (GA) combined with finite element method (FEM). The converters can realize the function of arbitrary ellipticity angle conversion of full polarization states. The size of the core device is only 1 μm $\times$ 1 μm, which is very conducive to high-density integration. The difference between the ideal output ellipticity angle and the actual output ellipticity angle of each device is no more than 2 degrees. In addition, it is proved that the use of optimization algorithms can easily design arbitrary-elliptical-polarization converters with different materials, different structures and different wavelengths, and the design of three-dimensional arbitrary-elliptical-polarization converters is also verified by using the optimization algorithm. This work provides an efficient design method for arbitrary polarization state conversion, showing its significance in improving the information capacity in optical communication.

Index Terms: Polarization converters, genetic algorithm, on-chip integration, Poincare sphere, finite element method.

1. Introduction

Nanophotonic devices, which take photon as information carriers, have the advantages of fast response, high integration, and strong anti-interference ability, which play important roles in the areas of all-optical computing, all-optical interconnection, and all-optical networks. A variety of nanophotonic devices have been designed in previous research [1], including wavelength-divided routing devices [2]–[5], all-optical logic gates [6]–[8], resonators [9], [10], power beam splitters [11], [12], and polarization devices [13]–[25]. Polarization, as a basic degree of freedom of light, is one of the most important properties of light. Polarization devices play significant roles in carrying and transmitting information, making them an essential component of nanophotonic devices.

There are many polarization devices designed by using traditional method of manually adjusting parameters, such as the use of three-dimensional asymmetric structure [13] and nano-groove structure [14] to achieve the function of splitting TM mode and TE mode, and the use of metasurface to realize the conversion between TE mode and TM mode [15]. However, with the increasing requirement of nanophotonic integration, the design of traditional manually adjusting parameters usually consume a lot of time and energy, and the performance of the designed devices is limited, so it is difficult to meet the development of nanophotonic integrated devices. In order to improve efficiency and expand device functionality, in recent years, there have been related reports of devices designed by algorithms, such as polarizer or polarization (de)multiplexer based on the direct-binary-search algorithm [16], [17], circular Hall sub-polarization device based on annealing algorithm and GA [18], wavelength and polarization division based on gradient-based optimization algorithm [19], and linear polarization converter based on GA [20]. However, the functions of the above devices are mostly focused on splitting three different polarization states or simply realize the polarization conversion in the range of linearly polarized light [14], [20], [21]. In order to achieve high-density and multi-function on-chip integration, optical devices are required to expand their functions while further reducing their size. It is an alternative way to use elliptical polarization in order to increase information capacity [22], [26]. However, existing elliptical polarization converters take advantage of transmission or reflection of metasurfaces, and convert light in free space, which are not easy to be compatible with on-chip integration [22]. Therefore, it is still a challenge to realize the high-efficiency design of on-chip ultra-small arbitrary-elliptical-polarization converters with different materials, different structures and different wavelengths.

In this letter, we design on-chip ultra-small arbitrary-elliptical-polarization converters based on an optimization algorithm, which combines the genetic algorithm (GA) with the finite element method (FEM). The converters can realize the function of arbitrary ellipticity angle conversion of full polarization states. The size of the device is only 1 μm $\times$ 1 μm, which is beneficial for photonic integration. The design method is universal, which is suitable for the design of polarization converter with different materials, different structures, and different wavelengths, and the design of three-dimensional arbitrary-elliptical-polarization converters is also verified by using the optimization algorithm. This work provides a new scheme for designing polarization devices with efficient calculations and high conversion efficiency, making full use of the polarization information. The proposed devices have wide applications in integrated nanophotonic devices.

2. Design Method

The polarization can be demonstrated on the Poincare sphere, which is defined as the unit sphere in the space of Stokes parameters S_1, S_2, S_3 [27]. Each point on the sphere uniquely represents one polarization state. The ellipticity and chirality of the polarization states are described by the ellipticity angle χ. As is shown in Fig. 1(a), the ellipticity angle χ is defined as half of the angle formed by the vector from the origin to the points on Poincare sphere and the S_1, S_2 plane. The sign of χ is positive at the north semi-sphere and negative at the south semi-sphere, which describes the chirality. Right-handed polarization states have positive χ and left-handed polarization states have negative χ. The absolute value of χ describes the ellipticity. It is related to the ratio of the semi-minor axis and the semi-major axis of the polarization ellipse by Eq. (1)

$$|\chi| = arctan\left(\frac{b}{a}\right) \tag{1}$$

where b, a are the lengths of the semi-minor axis and semi-major axis [22]. Specially, when $\chi = 0$, the polarization states are linear polarization, and when $\chi = \pm 45^\circ$, the polarization states are circular polarization.

The ellipticity angle can be directly calculated by Stokes parameters, but the calculation of Stokes parameters requires an orthogonal frame where the z axis is parallel to the energy flow. Here, we calculate the ellipticity angle by the complex amplitude of electric vector $\boldsymbol{E}$ and the Poynting vector

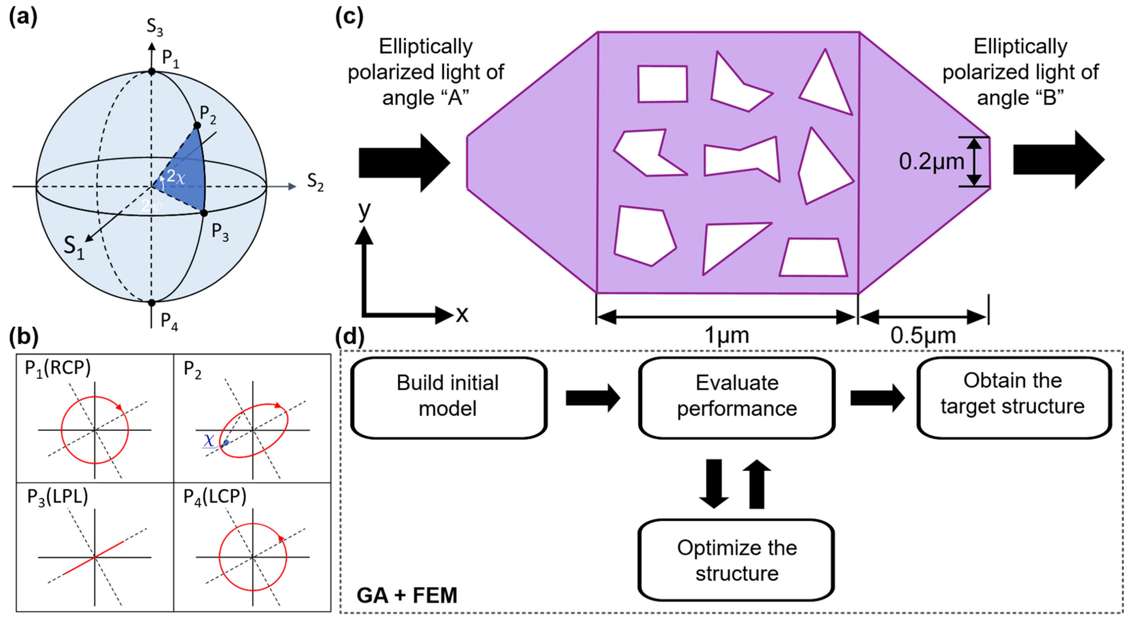

Fig. 1. (a) Diagram of Poincare sphere and the polarization states. χ denotes the ellipticity angle. (b) The polarization states at the four points P_1, P_2, P_3, P_4. (c) Schematic of the structure and the function of the device. (d) Flow chart for the optimization process.

S instead of Stokes parameters, as is shown in Eq. (2)

$$\chi = -\frac{1}{2} \, arcsin \left[\frac{2\left(Re\left(\boldsymbol{E}\right) \times Im\left(\boldsymbol{E}\right)\right) \cdot \boldsymbol{S}}{|\boldsymbol{S}|\,|\boldsymbol{E}|^2} \right] \tag{2}$$

where $Re(\boldsymbol{E})$ and $Im(\boldsymbol{E})$ represent the real and imaginary part of $\boldsymbol{E}$. Eq. (2) is equivalent to the method using Stokes parameters, but it only requires the vectors $\boldsymbol{E}$ and $\boldsymbol{S}$, which can be extracted directly from numerical calculation.

The ellipsometry is an important basis for judging the "ellipse degree" of polarized light. As shown in Fig. 1(b), if it is −45 degrees, it means this polarized light is right-handed circularly polarized light; else if it is between 0 degree and 45 or −45 degrees, it means that this polarized light is elliptically polarized light. If the angle calculated by this formula is 0 degree, it means that the polarized light is linearly polarized light, else if it is 45 degrees, it means that the polarized light is left-handed circularly polarized light.

The structure diagram and function of arbitrary-elliptical-polarization converters are shown in Fig. 1(c). The on-chip polarization converter device consists of a square region with dimension of 1 μm × 1 μm and two trapezoidal waveguides on the left and right side of it, and each end of the trapezoidal waveguide width is 0.2 μm. The middle region is the design region, where rectangle, triangle or any geometry shapes of different materials can be added for optimization in the subsequent calculation. The function of arbitrary-elliptical-polarization converters is that when an elliptically polarized light with a certain ellipticity angle A is incident, after passing through the design region, the elliptically polarized light with a specified ellipticity angle B will be output, where A and B can be any ellipticity angles, so that such structures can realize arbitrary-elliptical-polarization conversion.

The arbitrary-elliptical-polarization converters is designed by an optimization algorithm, which combines GA with FEM. The basic design steps are extracted and shown in Fig. 1(d). First, we establish a basic structure model by FEM. Second, FEM is used to simulate these models, and the fitness function of the algorithm is used to evaluate the performance of each model. Here, the fitness function used for evaluation is the absolute value of the difference between the ideal output

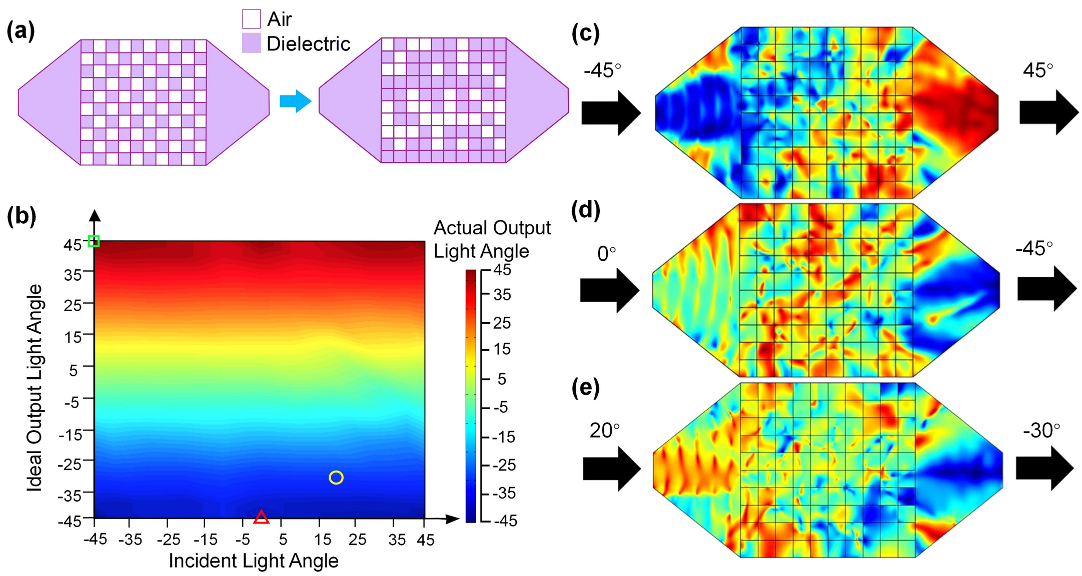

Fig. 2. (a) The changing process of structure during the iterative optimization process. (b) Rainbow image shows the function of all 121 mosaic structure devices. (c–e) Devices that realize the function of elliptical polarization conversion. Conversion of ellipticity angle (c) from −45° to 45° (d) from 0° to −45° (e) from 20° to −30°.

angle and the actual output angle. The output angle can be detected by a boundary probe of FEM at the right end of the right trapezoidal waveguide. The ideal output angle is the ellipticity angle of the desired model output, and the actual output light is the ellipticity angle of the output light of model. When the fitness function becomes smaller, it means that the actual output angle of the device is getting closer to the ideal output angle, and that the device can achieve better performance. Third, GA is used to iteratively optimize the device and repeat the evaluation and optimization process until the optimal solution is obtained. At last, the material distribution of structures will gradually become irregular towards the direction of reducing the fitness function during the iterative calculation process.

3. Various Arbitrary-Elliptical-Polarization Converters

From the definition of ellipticity angle, the range of incident angle and output angle is between −45 degrees and 45 degrees. In order to achieve arbitrary-elliptical-polarization converters covering full polarization states, 121 devices were calculated for the mosaic structure and the arbitrary hexagonal structure. The materials of the polarization converters can be determined according to actual needs, of which high refractive index materials are preferred, such as GaP, GaAs, GaN, etc. Here, a dielectric material with a refractive index of 3.45 and air with a refractive index of 1.0 are used to design the structure, and the wavelength is set to 630 nm.

3.1 Arbitrary-Elliptic-Polarization Converters with Different Structures

The structure of arbitrary-elliptic-polarization converter with mosaic structure is shown in the Fig. 2(a). The design region is divided into 100 equal parts, and then introduce a 100-dimension-matrix which consists of “0”s and “1”s. The 100 dimensions signify 100 units of design region, and “0” represents material air, and “1” represents a dielectric material with a refractive index of 3.45. The arrangements of “0” and “1” in the matrix symbolize the material distribution of the model.

Fig. 2(b) represents the performance of the mosaic structure devices. The x-coordinate in the figure denotes the designated ellipticity angle of the incident light. The y-coordinate denotes the

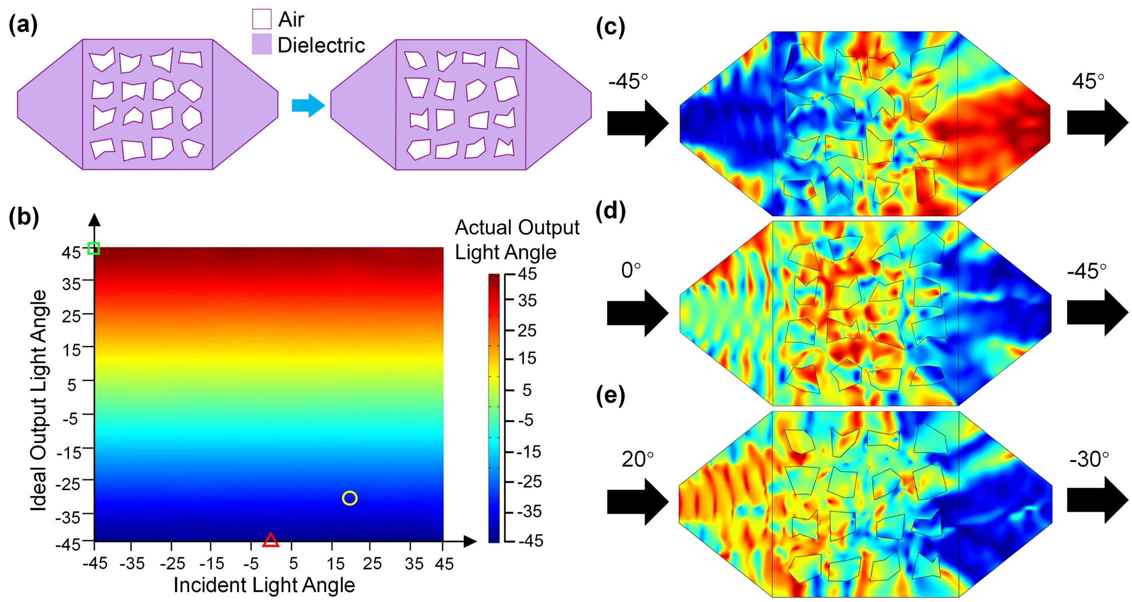

Fig. 3. (a) The changing process of structure during the iterative optimization process. (b) Rainbow image shows the function of all 121 arbitrary hexagon structure devices. (c–e) Devices that realize the function of elliptical polarization conversion. Conversion of ellipticity angle (c) from −45° to 45° (d) from 0° to −45° (e) from 20° to −30°.

ideal output angle of light, which means the ellipticity angle of the output light that the device needs to convert to. In other words, the designated ellipticity angle of the incident light and the ideal output light determine the function that the device achieve. The color of each pixel in this figure corresponds to the color scale on the right side. It represents the actual ellipticity angle of the output light, which is the simulation result of the optimized device achieved by the algorithm. The pixel point circled in green in Fig. 2(b) represents the device with the incident angle of −45 degrees, and the ideal output angle of 45 degrees, as shown in Fig. 2(c). The actual output angle of the device differs by 1.39 degrees from the ideal output angle, which means the actual output angle is 43.61 degrees. For the pixel point circled in red in Fig. 2(b), which has been shown in Fig. 2(d), it represents the device with the incident angle of 0 degree, and the ideal output angle of −45 degrees. The actual output angle of the device differs by 1.81 degrees from the ideal output angle, which means the actual output angle is −43.19 degrees. Similarly, Fig. 2(e) represents the device which has been circled in yellow in Fig. 2(b). This pixel point represents a device with the incident angle of 20 degrees, and the ideal output angle of −30 degrees. The actual output angle of the device differs by 0.19 degrees from the ideal output angle, which means the actual output angle is −29.81 degrees. The above results are achieved on a personal computer with Intel (R) Core (TM) i5-10210U CPU at 2.11 GHz, and 8 GB installed memory (RAM). In this circumstance, it takes less than 40 minutes for each device to get satisfying function.

The structure of arbitrary-elliptic-polarization converter with hexagonal structure is shown in the Fig. 3(a). The design region of this structure is divided into 4 $\times$ 4 units, and generate an irregular hexagon in each unit. The material of 16 hexagons is set as air, and the rest of the design region is a dielectric material with a refractive index of 3.45. The coordinates of the six vertices of each hexagon are set as variables, and then use the algorithm to determine all variables. The device performance of the arbitrary hexagon structure optimized by the algorithm is shown in Fig. 3(b). Compared with the mosaic structure of the rainbow image, it can be seen that the arbitrary hexagonal structure of the device has better performance. This is mainly because the structure receives less constraints, so it is easier to find devices with better performance when using algorithm design. As shown in Fig. 3(c), the pixel point circled in green in Fig. 3(b) indicates

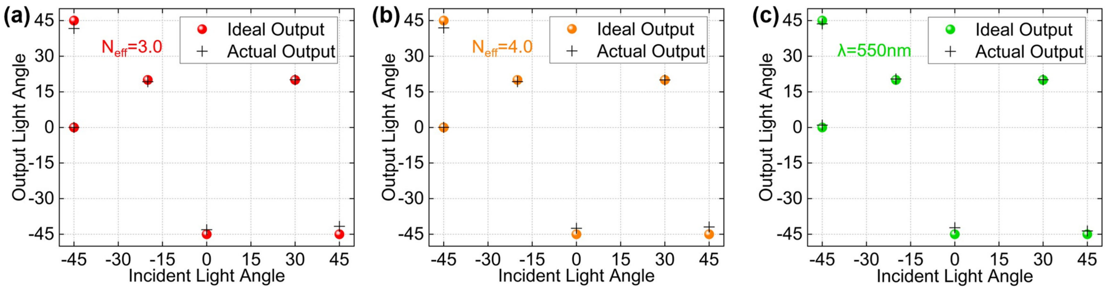

Fig. 4. (a) The function of the material with a refractive index of 3.0. (b) The function of the material with a refractive index of 4.0. (c) The function of the working wavelength 550 nm.

the device with the incident angle of −45 degrees, and the ideal output angle of 45 degrees. The actual output angle of the device differs by 0.73 degrees from the ideal output angle, which means the actual output angle is 44.27 degrees. Fig. 3(d) represents the device which has been circled in red in Fig. 3(b). This pixel point represents a device with the incident angle of 0 degrees, and the ideal output angle of −45 degrees. The actual output angle of the device differs by 0.83 degrees from the ideal output angle, which means the actual output angle is −44.17 degrees. The pixels circled in yellow in Fig. 3(b), which have been shown in Fig. 3(e), represent the device with an incidence angle of 20 degrees and an ideal output angle of −30 degrees. The actual output angle of the device differs by 0.03 degrees from the ideal output angle, which means the actual output angle is −29.97 degrees.

3.2 Elliptic Polarization Conversion for Different Materials and Different Wavelengths

In order to study the universality of the design method based on the constructed optimization algorithm, the mosaic structure is used to further calculate the ellipticity angle conversion of different materials and different wavelengths. Due to the high degree of freedom of the optimization algorithm, the structure, material and working band of the equipment can be set in a wide range, which means that the function of the device depends on the needs of the designer. As shown in Fig. 4, after changing the materials and working wavelength, the calculated results of the devices remain satisfying. Red points and orange points in Figs. 4(a) and 4(b) show the functions of some devices when the refractive index of the material is respectively 3.0 and 4.0, which proves that the manufacturing method of the device provided in this letter is also suitable for Materials with a refractive index other than 3.45. Besides, the wavelength of incident light can also change according to designers' need. As an example of that, the optimization results of working wavelength 550 nm are presented the green points in Fig. 4(c). This design method is reliable for different materials and different wavelengths.

3.3 Three-dimensional Arbitrary-Elliptic-Polarization Converter

Considering the practical applications, a 3D structure has been further designed and calculated based on the above algorithm to realize arbitrary-elliptic-polarization converter, as shown in Fig. 5(a). The three-dimensional arbitrary-elliptical-polarization converter is divided into two layers, the top layer (purple) is silicon with the thickness of 220 nm, and the bottom layer (gray) is silica with the thickness of 500 nm, and the hexagonal apertures (white) on silicon layer is air. The elliptically polarized light of angle *A* is incident and after passing through the design region, it is converted into elliptically polarized light of angle *B*.

Fig. 5(b) shows a device with an incidence angle of −45 degrees and an ideal output angle of 0 degrees, the right figure shows the elliptical polarization angle of the emitting part. The actual output angle of the device differs by 0.51 degrees from the ideal output angle, which means the

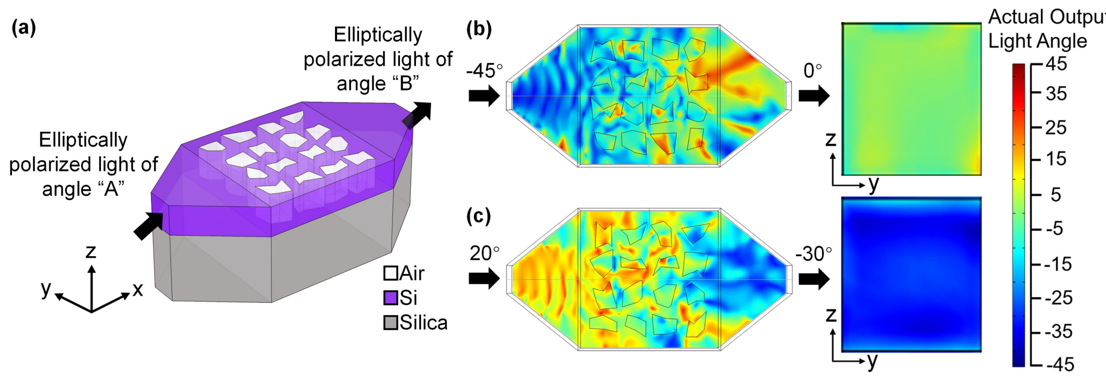

Fig. 5. (a) Three-dimensional arbitrary-elliptic-polarization converter structure. (b–c) Devices that realize the function of elliptical polarization conversion. Conversion of ellipticity angle (b) from −45° to 0° (c) from 20° to −30°.

actual output angle is −0.51 degrees. Fig. 5(c) shows a device with an incidence angle of 20 degrees and an ideal output angle of −30 degrees, the right figure shows the elliptical polarization angle of the emitting part. The actual output angle of the device differs by 0.09 degrees from the ideal output angle, which means the actual output angle is −30.09 degrees.

4. Conclusion

In conclusion, we have designed on-chip ultra-small arbitrary-elliptical-polarization converters based on optimization algorithm by combining GA and FEM. The function of the devices is the conversion of any ellipticity angle covering full polarization states, which can make full use of the polarization information carried by the polarized light. The device is designed as an on-chip structure with an ultra-small size of 1 μm × 1 μm, which is very conducive to high-intensity chip integration. Moreover, the optimization algorithm used to optimize the structure of device in the design process is universal, this method could be used to design devices with other structures, materials, and functions, which means it has broad application prospects in the design of photonic devices. This work provides an efficient way to realize nanophotonic arbitrary-elliptical-polarization converter based on optimization algorithms, and provides a new way for the realization of nanophotonic devices.

References

[1] K. Yao, R. Unni, and Y. Zheng, "Intelligent nanophotonics: Merging photonics and artificial intelligence at the nanoscale," *Nanophotonics*, vol. 8, no. 3, pp. 339–366, 2019.
[2] T. Tanemura *et al.*, "Multiple-wavelength focusing of surface plasmons with a nonperiodic nanoslit coupler," *Nano Lett.*, vol. 11, no. 7, pp. 2693–2698, 2011.
[3] C. Lu, H. Wang, J. Miao, W. Guo, X. Xiang, and Y. Liu, "A tunable on-chip integrated plasmonic filter and router based on metal/dielectric nanostructures," *Plasmonics*, vol. 13, no. 1, pp. 115–121, 2018.
[4] Z. Liu *et al.*, "Integrated nanophotonic wavelength router based on an intelligent algorithm," *Optica*, vol. 6, no. 10, pp. 1367–1373, 2019.
[5] A. Y. Piggott *et al.*, "Inverse design and demonstration of a compact and broadband on-chip wavelength demultiplexer," *Nature Photon.*, vol. 9, no. 6, pp. 374–377, 2015.
[6] Z. Zalevsky, and I. Abdulhalim, *Micro and Nano Technologies, Integrated Nanophotonic Devices*, 2nd ed., William Andrew Publishing, pp. 247, 2014.
[7] V. Jandieri, R. Khomeriki, and D. Erni, "Realization of true all-optical AND logic gate based on nonlinear coupled air-hole type photonic crystal waveguides," *Opt. Exp.*, vol. 26, no. 16, pp. 19845–19853, 2018.
[8] C. Lu, X. Hu, H. Yang, and Q. Gong, "All-optical logic binary encoder based on asymmetric plasmonic nanogrooves," *Appl. Phys. Lett.*, vol. 103, no. 12, 2013, Art. no. 075501.
[9] J. Lu, S. Boyd, and J. Vučković, "Inverse design of a three-dimensional nanophotonic resonator," *Opt. Exp.*, vol. 19, no. 11, pp. 10563–10570, 2011.

[10] L. J. Kauppinen *et al.*, "Micromechanically tuned ring resonator in silicon on insulator," *Opt. Lett.*, vol. 36, no. 7, pp. 1047–1049, 2011.
[11] K. Xu *et al.*, "Integrated photonic power divider with arbitrary power ratios," *Opt. Lett.*, vol. 42, no. 4, pp. 855–858, 2017.
[12] M. H. Tahersima *et al.*, "Deep neural network inverse design of integrated photonic power splitters," *Sci. Reports*, vol. 9, no. 1, p. 1368, 2019.
[13] Z. Ying, G. Wang, X. Zhang, H. Ho, and Y. Huang, "Ultracompact and broadband polarization beam splitter based on polarization-dependent critical guiding condition," *Opt. Lett.*, vol. 40, no. 9, pp. 2134–2137, 2015.
[14] C. Sun, H. Li, Q. Gong, and J. Chen, "Ultra-small and broadband polarization splitters based on double-slit interference," *Appl. Phys. Lett.*, vol. 108, no. 10, 2016, Art. no. 101106.
[15] Y. Tanaka, S. I. Takayama, and T. Asano, "A polarization diversity two-dimensional photonic-crystal device," *IEEE J. Sel. Topics Quantum Electron.*, vol. 16, no. 1, pp. 70–76, Jan./Feb. 2010.
[16] B. Shen, P. Wang, R. Polson, and R. Menon, "Ultra-high-efficiency metamaterial polarizer," *Optica*, vol. 1, no. 5, pp. 356–360, 2014.
[17] W. Chang *et al.*, "Ultra-compact mode (de) multiplexer based on subwavelength asymmetric Y-junction," *Opt. Exp.*, vol. 26, no. 7, pp. 8162–8170, 2018.
[18] Z. Xie, T. Lei, H. Qiu, Z. Zhang, H. Wang, and X. Yuan, "Broadband on-chip photonic spin hall element via inverse design," *Photon. Res.*, vol. 8, no. 2, pp. 121–126, 2020.
[19] P. Camayd-Muñoz, C. Ballew, G. Roberts, and A. Faraon, "Multifunctional volumetric meta-optics for color and polarization image sensors," *Optica*, vol. 7, no. 4, pp. 280–283, 2020.
[20] Z. Yu, H. Cui, and X. Sun, "Genetic-algorithm-optimized wideband on-chip polarization rotator with an ultrasmall footprint," *Opt. Lett.*, vol. 42, no. 16, pp. 3093–3096, 2017.
[21] S. E. Mun, J. Hong, J. G. Yun, and B. Lee, "Broadband circular polarizer for randomly polarized light in few-layer metasurface," *Sci. Reports*, vol. 9, no. 1, 2019, Art. no. 2543.
[22] Z. Shi *et al.*, "Continuous angle-tunable birefringence with freeform metasurfaces for arbitrary polarization conversion," *Sci. Adv.*, vol. 6, no. 23, Paper. eaba3367, 2020.
[23] M. J. Moghadam, M. Akbari, F. Samadi, and A. R. Sebak, "Wideband cross polarization rotation based on reflective anisotropic surfaces," *IEEE Access*, vol. 6, pp. 15919–15925, 2018.
[24] D. Dai, Z. Wang, J. Peters, and J. E. Bowers, "Compact polarization beam splitter using an asymmetrical Mach–Zehnder interferometer based on silicon-on insulator waveguides," *IEEE Photon. Technol. Lett.*, vol. 24, no. 8, pp. 673–675, Apr. 2012.
[25] J. Lu and J. Vučković, "Nanophotonic computational design," *Opt. Exp.*, vol. 21, no. 11, pp. 13351–13367, 2013.
[26] Y. Guo, M. Xiao, Y. Zhou, and S. Fan, "Arbitrary polarization conversion with a photonic crystal slab," *Adv. Opt. Mater.*, vol. 7, no. 14, pp. 1801453.1–1801453.8, 2019.
[27] M. Born, E. Wolf, and E. Hecht, "Principles of optics: Electromagnetic theory of propagation, interference and diffraction of light," *Phys. Today*, vol. 53, no. 10, pp. 77–78, 2000.