ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理 Chinese Physics B

Analysis of CV mode selected resonator based on vectorial eigenvector method

You-You Hu(胡友友), Jian-Tai Dou(窦健泰), Bo-Wei Luo(罗博伟), Chang-Yu He(贺昌玉)

Citation: Chin. Phys. B . 2019, 28(2): 024210. **doi:** 10.1088/1674-1056/28/2/024210
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Effect of thermally induced birefringence on high power picosecond azimuthal polarization Nd:YAG laser system

Hongpan Peng(彭红攀), Ce Yang(杨策), Shang Lu(卢尚), Ning Ma(马宁), Meng Chen(陈檬)
Chin. Phys. B . 2019, 28(2): 024205. **doi:** 10.1088/1674-1056/28/2/024205

Controllable transmission of vector beams in dichroic medium

Yun-Ke Li(李云珂), Jin-Wen Wang(王金文), Xin Yang(杨欣), Yun Chen(陈云), Xi-Yuan Chen(陈熙远), Ming-Tao Cao(曹明涛), Dong Wei(卫栋), Hong Gao(高宏), Fu-Li Li(李福利)
Chin. Phys. B . 2019, 28(1): 014205. **doi:** 10.1088/1674-1056/28/1/014205

Polarization-based range-gated imaging in birefringent medium:Effect of size parameter

Heng Tian(田恒), Jing-Ping Zhu(朱京平), Shu-Wen Tan(谭树文), Jing-Jing Tian(田晶晶), Yun-Yao Zhang(张云尧), Xun Hou(侯洵)
Chin. Phys. B . 2018, 27(12): 124203. **doi:** 10.1088/1674-1056/27/12/124203

Tunable plasmon-induced transparency based on asymmetric H-shaped graphene metamaterials

Yu-Chen Tian(田雨宸), Wei Jia(贾微), Pei-Wen Ren(任佩雯), Chun-Zhen Fan(范春珍)
Chin. Phys. B . 2018, 27(12): 124205. **doi:** 10.1088/1674-1056/27/12/124205

β-BaB_2O_4 with special cut-angle applied to single crystal cascaded third-harmonic generation

Hong-Kai Ren(任宏凯), Hong-Wei Qi(亓宏伟), Zheng-Ping Wang(王正平), Zhi-Xin Wu(吴志心), Meng-Xia Wang(王梦霞), Yu-Xiang Sun(孙玉祥), Xun Sun(孙洵), Xin-Guang Xu(许心光)
Chin. Phys. B . 2018, 27(11): 114202. **doi:** 10.1088/1674-1056/27/11/114202

Analysis of CV mode selected resonator based on vectorial eigenvector method*

You-You Hu(胡友友)[1], Jian-Tai Dou(窦健泰)[1], Bo-Wei Luo(罗博伟)[2], and Chang-Yu He(贺昌玉)[2,†]

[1] *Department of Physics, College of Science, Jiangsu University of Science and Technology, Zhenjiang* 212003, *China*
[2] *School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan* 430074, *China*

(Received 18 October 2018; revised manuscript received 19 November 2018; published online 10 January 2019)

The vectorial eigenvector method was applied to compute the cylindrical vector (CV) modes of polarization-dependent resonators and multiple modes in the CV mode selected resonator were tracked. Then, the mode characteristics of CV mode selected resonator depending on the Fresnel number, geometry parameters, and polarization parameters were simulated. When the difference in reflection coefficient between radial and azimuthal polarization is greater than 0.021 for spherical semi-confocal cavity, the radially polarized TM_{01*} mode most probably appears in the resonator due to its lowest loss, which is consistent with an azimuthal polarization-selective resonant cavity. Moreover, the appropriate phase shift factor contributes to suppress non-rotationally symmetrical modes, which promotes the selection of CV modes. The Fresnel number between 2 and 2.5 are the appropriate range of values when the value of geometry parameters g_2 is 0.5, both of which decide the effective Fresnel number.

Keywords: laser resonators, polarization, polarization-selective devices, lasers and laser optics

PACS: 42.60.Da, 42.25.Ja **DOI:** 10.1088/1674-1056/28/2/024210

1. Introduction

Due to the special polarization distribution of cylindrical symmetry, cylindrical vector beams (CVBs), such as azimuthally polarized beams (APBs) and radially polarized beams (RPBs), are of importance for the applications of electron acceleration,[1] optical trapping,[2] optical microscopy,[3] optical storage,[4] laser processing,[5,6] plasmon excitation,[7,8] and so on. A high power radially polarized laser is superior in industrial applications, and can improve the speed and quality of laser cutting.[5] These advantages of cylindrical vector beams have led to the production of high power radially polarized beams and azimuthally polarized beams.

Many methods of generating cylindrical vector beams have been explored,[9–20] and can be divided into two categories: intra- and extra-cavity methods. Among them, polarization-selective diffraction grating mirror and axicon are commonly utilized as rear mirrors to generate high power cylindrical vector beams directly in the resonator[14–16,19] because of their superior thermal stability and polarization selectivity. For these cylindrical vector mode selected resonators, the laser dynamics of the selecting cylindrical vector mode by mode competition and the cylindrical vector mode distribution are very significant for the generation and application of the cylindrical vector beams.

In the present study, based on our previous investigations,[20] the vectorial eigenvector method (VEM) was utilized to compute the eigenmodes of the cylindrical vector mode selected resonators, which can derive lots of eigenmodes at a time, including scalar modes and vectorial modes. The multiple eigenmodes of the resonator were then tracked, which makes it possible to analyze the mode competition in the laser cavity. The mode characteristics depending on the Fresnel number, the geometry parameters and the polarization parameters were also simulated. The simulation results will be used to guide the design of the cylindrical vector mode selected resonators.

2. Vectorial eigenvector method

In our previous work, we presented the vectorial eigenvector method (VEM) to compute the eigenmodes in the resonator.[20] The vectorial eigenvector method is based on finite element method and evolved from scalar eigenvector method. New transmission matrices of laser resonant cavities with polarization-selective devices are built using Jones matrix representation. According to Jones vector theory, $U_1(x,y)$ and $U_2(x,y)$, the fields distributions on the mirror 1 and the mirror 2, can be discretized into a column vector, consisting of x-direction and y-direction components. Then, we can establish the following relationship:

*Project supported by the National Natural Science Foundation of China (Grant No. 61308045) and the National Science and Technology Cooperation Project (Grant No. 2014DFR10870).

†Corresponding author. E-mail: cyhe@hust.edu.cn

© 2019 Chinese Physical Society and IOP Publishing Ltd

$$\begin{bmatrix} u_{2x}[1] \\ u_{2x}[2] \\ \cdots \\ u_{2x}[g] \\ u_{2y}[1] \\ u_{2y}[2] \\ \cdots \\ u_{2y}[g] \end{bmatrix} = \begin{bmatrix} A_{12x}[1,1] & A_{12x}[2,1] & \cdots & A_{12x}[s,1] & 0 & 0 & \cdots & 0 \\ A_{12x}[1,2] & A_{12x}[2,2] & \cdots & A_{12x}[s,2] & 0 & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{12x}[1,g] & A_{12x}[2,g] & \cdots & A_{12x}[s,g] & 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & A_{12y}[1,1] & A_{12y}[2,1] & \cdots & A_{12y}[s,1] \\ 0 & 0 & \cdots & 0 & A_{12y}[1,2] & A_{12y}[2,2] & \cdots & A_{12y}[s,2] \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & 0 & A_{12y}[1,g] & A_{12y}[2,g] & \cdots & A_{12y}[s,g] \end{bmatrix} \begin{bmatrix} u_{1x}[1] \\ u_{1x}[2] \\ \cdots \\ u_{1x}[s] \\ u_{1y}[1] \\ u_{1y}[2] \\ \cdots \\ u_{1y}[s] \end{bmatrix}, \quad (1)$$

where $u_{2x}[n]$ and $u_{2y}[n]$, the n-th components of U_{2x} and U_{2y}, are the superposition of the fields produced by the fields of all elements of mirror 1. The factor $A_{12p}[m,n]$ $(p = x,y)$, derived from vector Rayleigh–Sommerfeld diffraction integral of paraxial approximation, is written as[21]

$$A_{12p}[m,n] = -\mathrm{i}\frac{\exp(\mathrm{i}kz)}{\lambda z}\iint_{S_m}\exp\left\{\frac{\mathrm{i}k}{2z}\left[(x-x_0)^2+(y-y_0)^2\right]\right\}\mathrm{d}x_0\mathrm{d}y_0, \quad \begin{pmatrix} m=1,2,\ldots,s \\ n=1,2,\ldots,g \end{pmatrix}, \quad (2)$$

where S_m and S_n are the integral area of the m-th and n-th element on mirrors 1 and 2, respectively. Then, we can obtain the transfer matrices A_{12} from mirror 1 to mirror 2, as well as transfer matrices A_{21} from mirror 2 back to mirror 1. For the CV mode selected resonator, matrices of polarization selective device (P_1) and coordinate transformation between Cartesian and cylindrical coordinate system (T_1) should be established.[19] Thus, the total transfer matrix can been expressed as

$$A = A_{21}T_1^{\mathrm{T}}P_1T_1A_{12}. \quad (3)$$

So, under self-reproducing condition, we can obtain all eigenmodes by solving complex eigenvectors and eigenvalues (γ) of the total transfer matrix of the CV mode selected resonator.

The VEM can derive lots of modes at a time, including scalar modes and vector modes. Each discrete unit is independent, so we can solve the mode of resonator with the Parallel Computing Toolbox in MATLAB, which improves the calculation speed by three times.

3. Analysis of CV mode-selected resonator

3.1. Mode characteristics

As shown in Fig. 1, a representative CV mode selected spherical semi-confocal cavity is simulated with resonator parameters: diameter of the circular planar mirror 1 and polarization-selective spherical mirror 2 of $2a = 20$ mm, radius of the spherical mirror 2 of $R_2 = 10$ m, reflection coefficients and phase shift factor of azimuthal and radial polarization of $R_{\mathrm{te}} = 0.93$, $P_{\mathrm{te}} = 0$, $R_{\mathrm{tm}} = 0.99$, and $P_{\mathrm{tm}} = 0$ respectively, resonator length of $L = 5$ m and wavelength of $\lambda = 10.6$ μm. Then, the Fresnel number and geometric parameters of the resonator are $F = a^2/\lambda L = 1.887$, $g_1 = 1$, and $g_2 = 0.5$. The calculated modes of the three largest $|\gamma|$ are given in Table 1.

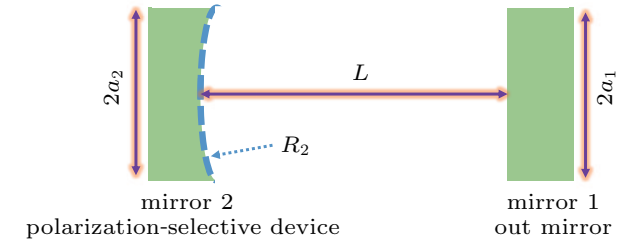


Fig. 1. Spherical semi-confocal cavity.

The degree of polarization (DP) of beams with axial polarization is given by[5]

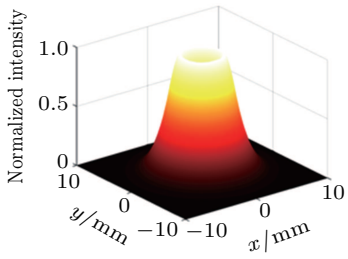
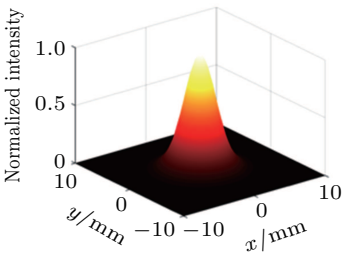
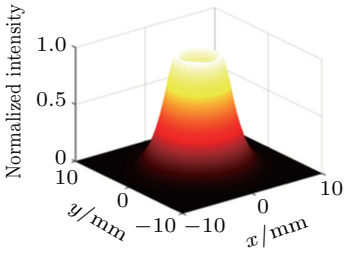
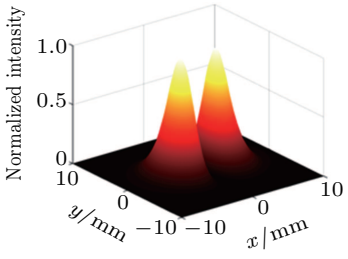
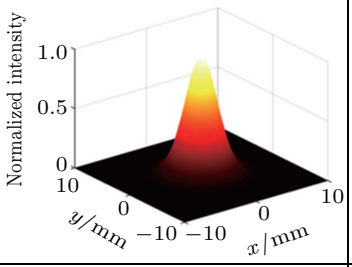
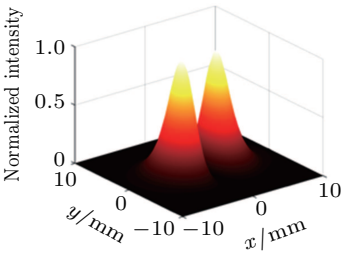
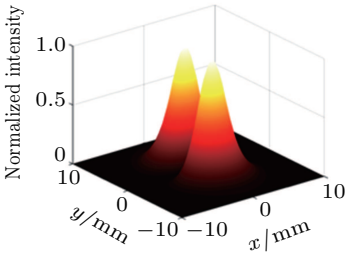
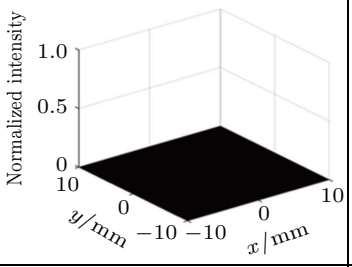
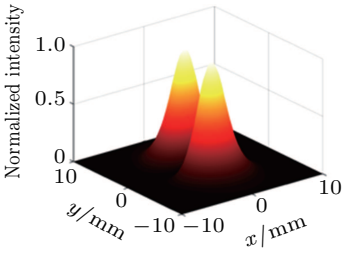
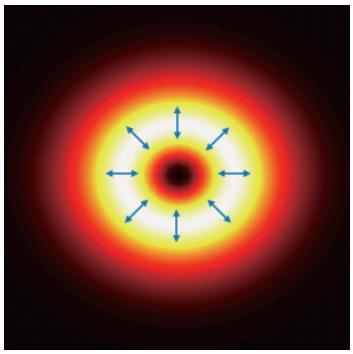
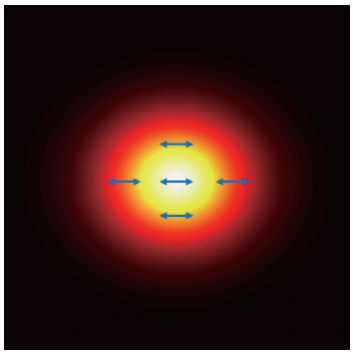
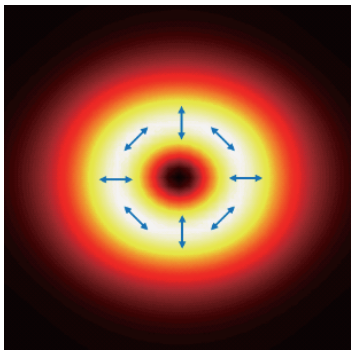
$$\mathrm{DP} = \frac{(I_{\mathrm{r}} - I_\phi)}{(I_{\mathrm{r}} + I_\phi)}, \quad (4)$$

where I_{r} and I_ϕ are the intensities of radial and azimuthal optical field components. $\mathrm{DP} = 1$ and $\mathrm{DP} = -1$ mean completely radial and azimuthal polarization respectively. The Stokes vector is used to detect the polarization state of the modes. According to the results of calculation, we can find that TM_{01*} mode, TEM_{00} mode and TEM_{01*} mode are the eigenmodes of the CV mode selected resonator and TM_{01*} most possibly appears in the cavity due to its lowest loss.

3.2. Influence of resonator parameters

We separately change each parameter of the resonator to further study the influence of the Fresnel number, geometry parameters and polarization parameters of the CV mode selected resonator on the mode characteristics of the resonator, which is called the control variable method. Unless otherwise specified, the default parameters are the same as used previously. Then, we track each mode and its complex eigenvalue of the resonator.

Table 1. Optical field distribution corresponding to the eigenvalues with $R_{te} = 0.99$ and $R_{tm} = 0.93$.

No.	1	2	3
$\|\gamma\|$	0.97844	0.95906	0.94865
Optical field distribution			
Distribution of I_x			
Distribution of I_y			
Polarization distribution			
DP	−1	0	0

3.2.1. Influence of polarization parameters

Commonly, for CV mode selected resonator, the modes depend on the difference of reflection coefficients between azimuthal and radial polarization; *i.e.*, $\Delta R = R_{tm} - R_{te}$. Thus, we set the parameters of polarization-selective device that $R_{te} = 0.95$ or 0.9 and let ΔR increase from 0 to 0.05 by an interval of 0.001. The calculated modes of the three largest $|\gamma|$ are listed in Table 2.

When $R_{te} = R_{tm} = 0.95$, the CV mode-selected resonator degenerates to ordinary polarization insensitive resonator. Although TEM_{00} mode, TM_{01*} mode and TEM_{01*} mode are all the eigenmodes when $R_{tm} = 0.97$, TEM_{00} mode will establish oscillation in the resonator. However, the loss of TM_{01*} mode becomes the lowest one when $R_{tm} = 0.99$. As illustrated in Fig. 2, the calculated $|\gamma|$ of the three largest values linearly increase with ΔR. The $|\gamma|$ of TEM_{00} mode is greater than that of TM_{01*} mode when $\Delta R < 0.021$. However, the slope of the $|\gamma|$ of TM_{01*} mode is relatively large. When $\Delta R > 0.021$, $|\gamma|$ of TM_{01*} mode is greater than that of TEM_{00} mode. Thus, it is concluded that the value of ΔR should be greater than 0.021 for selecting CV mode in the resonator.

Table 2. Optical field distribution corresponding to the eigenvalues with $R_{te} = 0.95$.

No. / R_{tm}	1	2	3
0.95	$\|\gamma\| = 0.94913$, DP $= 9.9898\text{T}10^{-17}$	$\|\gamma\| = 0.9393$, DP $= 0.013742$	$\|\gamma\| = 0.88902$, DP $= 2.1334\text{T}10^{-14}$
0.97	$\|\gamma\| = 0.95912$ DP $= 0.00033758$	$\|\gamma\| = 0.95908$, DP $= 0.99999$	$\|\gamma\| = 0.94918$, DP $= 0-.0036336$
0.99	$\|\gamma\| = 0.97885$, DP $= 0.99999$	$\|\gamma\| = 0.96909$, DP $= -0.0041088$	$\|\gamma\| = 0.95902$, DP $= -0.0064244$

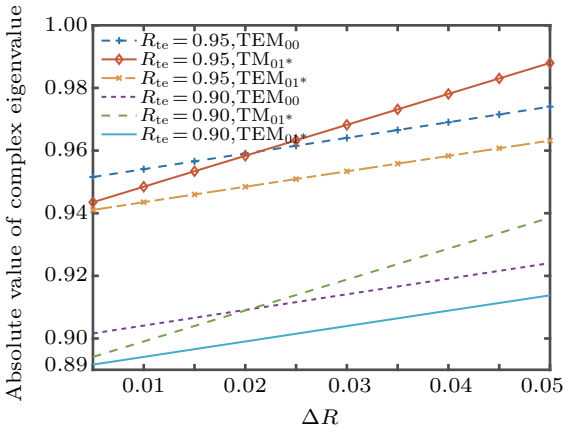


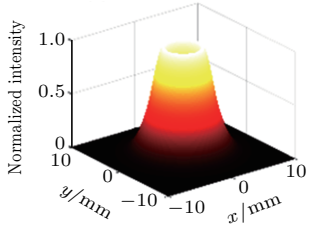
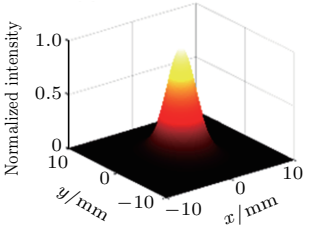
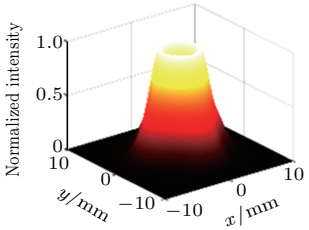
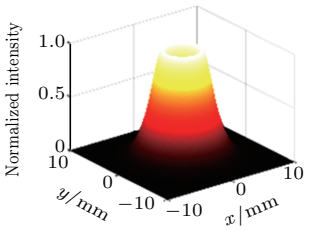
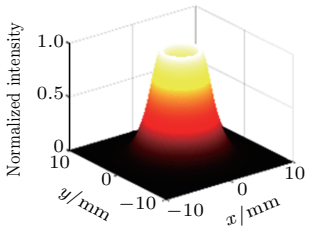
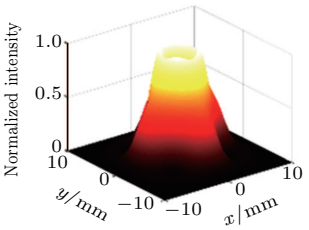
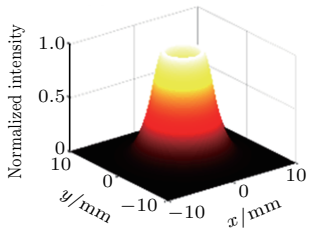
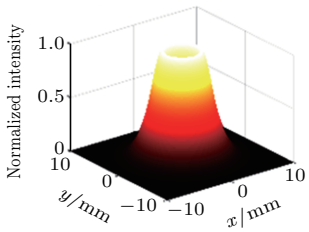
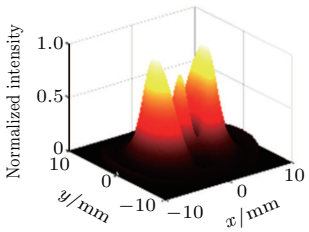
Fig. 2. Relationship between polarization selective parameters and $|\gamma|$.

In addition, phase shift factor is also an important parameter of polarization-selective device. Then, P_{te}, the phase shift factor of TE polarization, is assigned the value of 0 and the reasonable ranges of P_{tm}, the phase shift factor of TM polarization, are chosen from 0 to 2π. The calculated results based on VEM are listed in Table 3.

From the Table 3, we can find that the $|\gamma|$ of TM$_{01*}$ mode, the lowest loss eigenmode of the resonator, is dependent on phase shift factor. However, $|\gamma|$ of the second lowest loss eigenmode (C-TM$_{01*}$), TEM$_{00}$ mode or TE$_{01*}$ mode, changes with phase shift factor, which has a direct impact on mode competition.

As shown in Fig. 3, the $|\gamma|$ of C-TM$_{01*}$ mode has a period of 2π and there is a peak around $\pm 2m\pi$ ($m = 0, \pm 1, \pm 2, \ldots$), where C-TM$_{01*}$ mode is TEM$_{00}$ mode. While C-TM$_{01*}$ mode of flat area is TE$_{01*}$ mode. Thus, we think that the appropriate phase shift factor helps to suppress non-rotationally symmetrical mode.

Table 3. Optical field distribution corresponding to the eigenvalues with $P_{te} = 0$.

No. / P_{tm}	1	2	3
$\pi/8$	$\lvert\gamma\rvert = 0.97885$, DP $= 0.99999$ 	$\lvert\gamma\rvert = 0.94489$, DP $= -0.077162$ 	$\lvert\gamma\rvert = 0.9381$, DP $= -0.12586$ 
$\pi/4$	$\lvert\gamma\rvert = 0.97885$, DP $= 0.99999$ 	$\lvert\gamma\rvert = 0.91953$, DP $= 0.99999$ 	$\lvert\gamma\rvert = 0.9059$, DP $= -0.22879$ 
$\pi/2$	$\lvert\gamma\rvert = 0.97885$, DP $= 0.99999$ 	$\lvert\gamma\rvert = 0.91953$, DP $= -0.99999$ 	$\lvert\gamma\rvert = 0.82045$, DP $= 0.63329$ 

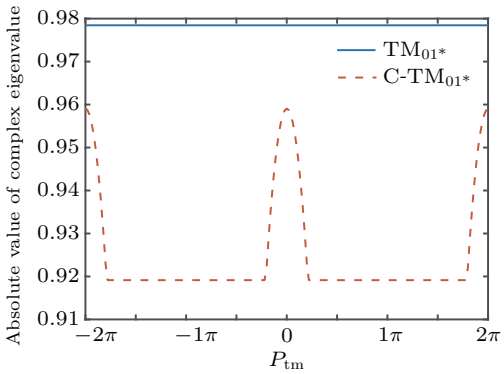
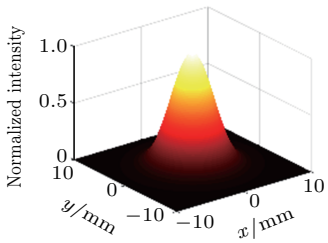
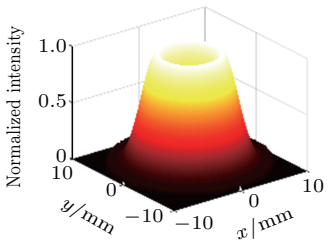
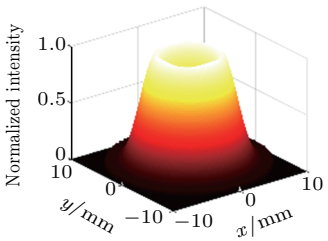
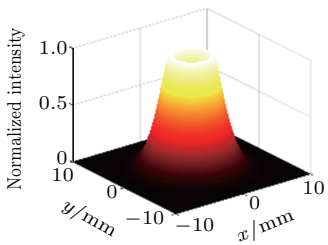
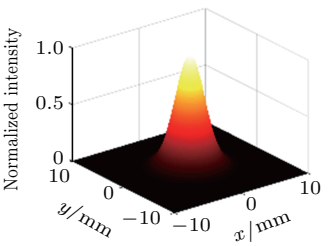
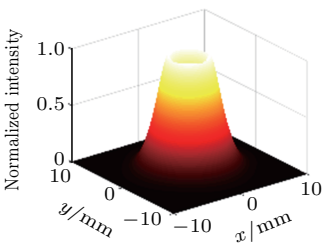
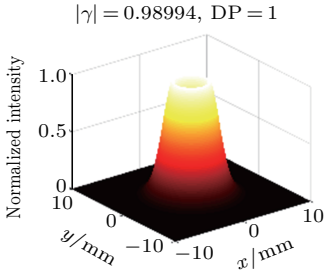
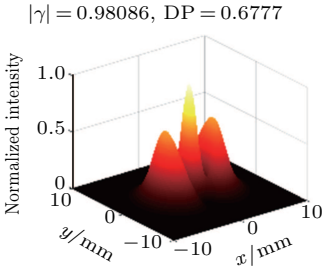
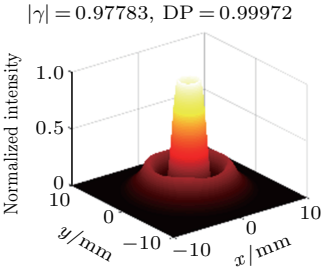


Fig. 3. Relationship between phase shift factor and $|\gamma|$.

3.2.2. Influence of Fresnel number

The Fresnel number is an important parameter of the resonator, which determines the loss of eigenmodes within the resonance. We control the change of the Fresnel number by changing the size of the aperture. As shown in Table 4, when $F = 1$, it is the TEM_{00} mode that the loss is the smallest, of which TM_{01*} mode replace the position while $F = 2$. Thus, larger Fresnel number contributes selecting CV mode in CV mode-selected resonator. As shown in Fig. 4, we can find that $|\gamma|$ monotonically increase with the Fresnel number and gradually approaches the maximum value. It also reveals that larger Fresnel number favors the selection of CV mode within the CV mode selected resonator. However, the supernumerary calculation results show that the Fresnel number cannot be increased indefinitely. With the increase of Fresnel number, $|\gamma|$ of the higher order mode will gradually increase and dominate the resonator. Consequently, it is appropriate to set the Fresnel number of CV mode selected semi-confocal cavity about 2.5.

Table 4. Optical field distribution corresponding to the eigenvalues with $g_2 = 0.5$.

No. / F	1	2	3
1.0	$\lvert\gamma\rvert = 0.90705$, DP $= -0.064559$ 	$\lvert\gamma\rvert = 0.71892$, DP $= 0.99996$ 	$\lvert\gamma\rvert = 0.69704$, DP $= -0.018338$ 
2.0	$\lvert\gamma\rvert = 0.98239$, DP $= 0.99999$ 	$\lvert\gamma\rvert = 0.95945$, DP $= -0.0994712$ 	$\lvert\gamma\rvert = 0.95299$, DP $= -0.0099669$ 
3.0	$\lvert\gamma\rvert = 0.98994$, DP $= 1$ 	$\lvert\gamma\rvert = 0.98086$, DP $= 0.6777$ 	$\lvert\gamma\rvert = 0.97783$, DP $= 0.99972$ 

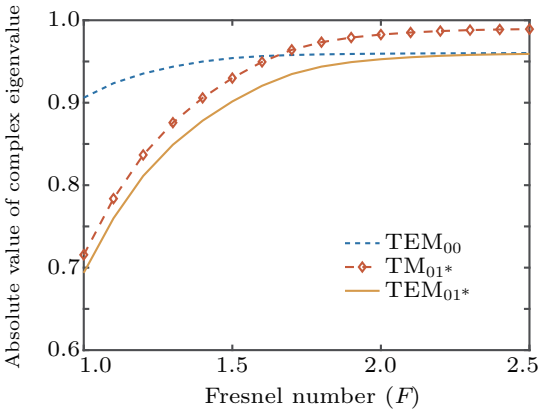


Fig. 4. Relationship between Fresnel number and $|\gamma|$.

3.2.3. Influence of geometric parameters

The geometric parameters describe the facet of the resonant cavity, which is applied to describe and analyze the resonator. For CV mode selected resonator, the geometric parameters also has an important effect on the selection of CV modes. The partial calculation results and the relationship between geometry parameters and $|\gamma|$ when the geometry parameter changes between 0 and 1 are shown in Table 5 and Fig. 5, respectively. The trend of the curve is consistent with the effective Fresnel number of mirror 2. For the default parameters of this article, $g_2 = 0.5$ is suitable due to the maximum effective Fresnel number.

Table 5. Optical field distribution corresponding to the eigenvalues with $F = 1.887$.

No. / g_2	1	2	3
0.3	$\|\gamma\| = 0.95398$, DP $= 0.0016505$	$\|\gamma\| = 0.95023$, DP $= 0.99998$	$\|\gamma\| = 0.92122$, DP $= -0.0088$
0.5	$\|\gamma\| = 0.97885$, DP $= 0.99999$	$\|\gamma\| = 0.95906$, DP $= -0.0080337$	$\|\gamma\| = 0.94904$, DP $= -0.009332$
0.7	$\|\gamma\| = 0.95291$, DP $= -0.037984$	$\|\gamma\| = 0.95221$, DP $= 0.99999$	$\|\gamma\| = 0.92319$, DP $= -0.00631$

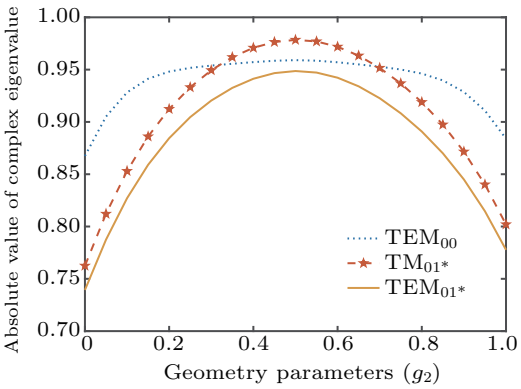


Fig. 5. Relationship between geometry parameters and $|\gamma|$.

In summary, the VEM is used to study the influences of the polarization parameters, Fresnel number and geometry parameters of the polarization-sensitive resonator on the CV mode selection. The calculated results are utilized to guide our design of a high power radially polarized CO_2 laser.[22]

4. Conclusions

In this paper, the VEM was applied to compute the modes of polarization dependent resonators and multiple modes in the CV mode selected resonator were tracked. Then, the mode characteristics depending on the polarization parameters, Fresnel number and geometry parameters were simulated. For above-mentioned CV mode selected spherical semi-confocal resonator, $\Delta R \geq 0.021$, radially polarized mode TM$_{01*}$ most probably appears in the resonator due to its lowest loss, which is consistent with azimuthal polarization-selective resonant cavity. Moreover, the appropriate phase shift factor contributes to suppress non-rotationally symmetrical mode, which promotes the selection of CV modes. Fresnel numbers between 2 and 2.5 are the appropriate range of values and $g_2 = 0.5$ is suitable, both of which decide the effective Fresnel number. The study of CV mode selected resonator has significance for the design of a polarization dependent resonator and can help to generate high power CV beams.

References

[1] Martens A, Dupraz K, Cassou K, Delerue N, Variola A and Zomer F 2014 *Opt. Lett.* **39** 981
[2] Cui W, Song F, Song F, Ju D and Liu S 2016 *Opt. Express* **24** 20062
[3] Chen W and Zhan Q 2007 *Opt. Express* **15** 4106
[4] Li X, Cao Y, Tian N, Fu L and Gu M 2015 *Optica* **2** 567

[5] Niziev V G and Nesterov A V 1999 *J. Phys. D: Appl. Phys.* **32** 1455
[6] Meier M, Romano V and Feurer T 2007 *Appl. Phys. A* **86** 329
[7] Zhang X and Yan L 2016 *Plasmon* **11** 109
[8] Lu Y Q, Hu S L, Lu Y, Xu J and Wang J 2015 *Acta Phys. Sin.* **64** 097301 (in Chinese)
[9] Stadler M and Schadt M 1996 *Opt. Lett.* **21** 1948
[10] Oron R, Blit S, Davidson N, Friesemt A A, Bomzon Z and Hasman E 2000 *Appl. Phys. Lett.* **77** 3322
[11] Bomzon Z, Biener G, Kleiner V and Hasman E 2002 *Opt. Lett.* **27** 285
[12] Kozawa Y and Sato S 2005 *Opt. Lett.* **30** 3063
[13] Chen H, Ling X, Chen Z, Li Q, Lv H, Yu H and Yi X 2016 *Chin. Phys. B* **25** 074201
[14] Nesterov A V, Niziev V G and Yakunin V P 1999 *J. Phys. D: Appl. Phys.* **32** 2871
[15] Moser T, Balmer J, Delbeke D, Muys P, Verstuyft S and Baets R 2005 *Appl. Phys. B* **80** 707
[16] Kämpfe T, Tonchev S, Tishchenko A V, Gergov D and Parriaux O 2012 *Opt. Express* **20** 5392
[17] Machavariani G, Lumer Y, Moshe I, Meir A, Jackel A and Davidson N 2007 *Appl. Opt.* **46** 3304
[18] Yi X, Ling X, Zhang Z, Li Y, Zhou X, Liu Y, Chen S, Luo H and Wen S 2014 *Opt. Express* **22** 17207
[19] Zhan Q 2009 *Adv. Opt. Photon.* **1** 1
[20] Hu Y, He X, Liu S, Tang X and Li B 2017 *Opt. Express* **25** 5186
[21] Hu Y, Tang X and Li B 2017 *Proc. SPIE* **10457** 104571D
[22] Li B, Hu Y, Hu Y and Zhao J 2017 *Appl. Opt.* **56** 3383