Improved method for analyzing quasi-optical launchers

Wu Ze-Wei(吴泽威)†, Li Hao(李 浩), Xu Jian-Hua(徐建华),
Li Tian-Ming(李天明), and Li Jia-Yin(李家胤)

School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054, *China*

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An improved method for analyzing the radiation characteristic of the quasi-optical launcher is presented. The launcher is decomposed into an open-ended waveguide and a helical cut according to the proposed method. The radiation from the open-ended waveguide is obtained by using the Stratton–Chu formulation. The helical cut's radiation is calculated based on its current distribution, gained by several iterative computations, which helps to improve the calculation accuracy since the diffraction effect introduced by the helical cut is considered during the calculation. The proposed method is used to study different launches, and the results are compared with the existing results. Good agreement is achieved between the results obtained from our proposed method and the reported results. The present results provide an alternative for analysis and synthesis of the optical-mode converter.

Keywords: gyrotron, quasi-optical launcher, Stratton–Chu formulation

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1. Introduction

Modern gyrotrons are important high-power sources of microwaves in the millimeter and sub-millimeter wavelength ranges.[1–4] An important constituent of gyrotrons is the quasi-optical mode converter which consists of a waveguide launcher and a few reflecting mirrors. The waveguide launcher converts the high-order gyrotron cavity mode into a fundamental Gaussian field distribution, which is further shaped by the following mirror.[5–8] In order to minimize the diffraction loss and cross-polarization inside the gyrotron, the launcher and the reflectors have to be designed carefully.

Currently, several methods have been proposed to synthesize and analyze gyrotron launchers: analytical methods,[9–12] formulation of the scalar integral equation (SIE),[13–16] and the magnetic field integral equation (MFIE).[17] For the analytical method, assuming that the field distribution on the cut is unperturbed by the process of opening up the waveguide, the radiated fields are calculated from the waveguide cut using the Stratton–Chu formulation according to the closed waveguide solution, which is obtained from the coupled mode theory. Such a method is valid when the surface currents along the cut are negligible but introduces errors in the evaluations when they are not. As the increase of the average power of gyrotron, the calculation error will amplify the internal loss, which results in the increase of the construction complexity and the expense of the gyrotron. The application requirements for the launcher have motivated the development of novel methods for the design of the launcher. The SIE in different forms are proposed. These methods could calculate the fields on waveguide walls with arbitrary surface deformations efficiently in a case of the perturbations are much smaller than radius and the waveguide is greatly oversized.[13,14] However, for these relatively low-order modes such as $TE_{6,2}$, $TE_{5,3}$,[18,19] which operate in a weakly oversized waveguide, the efficiency of the SIE still need further investigations since no results have been published up to now as far as we know. The MFIE method ensures the most accurate calculation of the three dimensional (3D) electromagnetic system based on the Maxwell equations, but is the most computationally intensive. Consequently, this method takes the longest calculation time even if the fast multipole technique is adopted. During the application, the analytical method and the SIE are usually used to synthesize the profile of the waveguide launcher, and all characteristics of the launcher including calculations of reflection and cross-polarization are verified by the MFIE.[19,20]

In this paper, an improved method is proposed to analyze the radiation performance of the quasi-optical launcher. Since the different parts of the launcher are calculated using different calculation methods, the amount of calculation for the proposed is reduced greatly compared with the MFIE. Meanwhile, the diffraction effect is considered during the vector integral calculation, the computational accuracy of the proposed method is ensured. Based on the proposed method, we have performed calculations for a Vlasov launcher and a Denisov launcher, and the calculations are compared with the reported results. The paper is organized as follows. The theory analysis is described in Section 2, the calculation results and comparison are given in Section 3, Section 4 shows the conclusion.

†Corresponding author. E-mail: wzw.198704@163.com

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2. Theoretical analysis

The launcher consists of a cylindrical waveguide (region I) and a helical cut (region II) as shown in Fig. 1(a). According to the geometrical optical theory for the waveguide, the propagation of a TE mode in the launcher could be described as an infinite number of rays reflecting on the inner surface of the waveguide following a certain helical.[8,21] Figure 1(b) illustrates the unfolded inner surface of the mode converter, where these rays reflect from one parallelogram (e.g., ABDC) to another parallelogram (e.g., CDFE), and repeat reflection while they propagate in the axial direction.

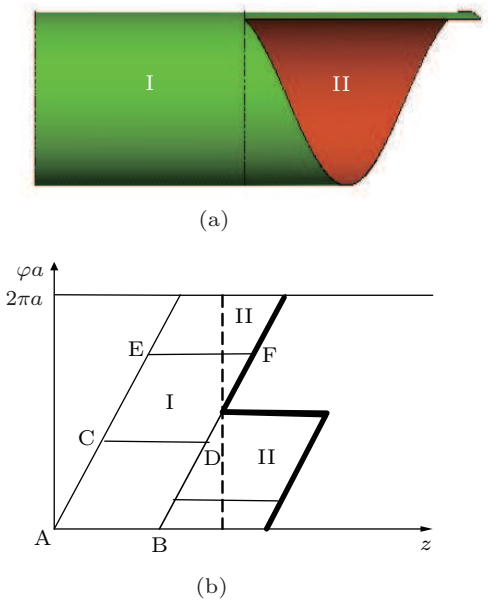


Fig. 1. (color online) (a) The scheme of launcher. (b) The unfolded launcher surface.

As the rays propagate along the cylindrical waveguide, they enter a helical cut. The helical cut perturbs the fields from those calculated using the closed waveguide solution. While for the cylindrical waveguide, its field distribution will not be disturbed because that the reflection of the launcher is required to be ignored. Therefore, the radiation from the launcher could be represented in terms of radiation field by the circular waveguide and the helical cut. To evaluate the fields radiated by the launcher, we take advantage of the well-known fact that the value of the fields at any other point of the free space can be obtained in integral forms using the Stratton–Chu theory. For region I, since the field on the waveguide wall could be obtained by the coupled mode theory, the radiated field $E_{\rm pI}$ and $H_{\rm pI}$ are derived by the Strantton–Chu formulation directly

$$\begin{cases} E_{\rm pI} = \dfrac{1}{4\pi {\rm j}\omega\varepsilon}\displaystyle\int_{\Omega}[k^2(\boldsymbol{n}\times\boldsymbol{H}_{\Omega})\varphi + (\boldsymbol{n}\times\boldsymbol{H}_{\Omega})\cdot\nabla(\nabla\varphi) \\ \qquad + {\rm j}\omega\varepsilon(\boldsymbol{n}\times\boldsymbol{E}_{\Omega}\times\nabla\varphi)]{\rm d}\Omega, \\ H_{\rm pI} = \dfrac{-1}{4\pi {\rm j}\omega\mu}\displaystyle\int_{\Omega}[k^2(\boldsymbol{n}\times\boldsymbol{E}_{\Omega})\varphi + (\boldsymbol{n}\times\boldsymbol{E}_{\Omega})\cdot\nabla(\nabla\varphi) \\ \qquad + {\rm j}\omega\varepsilon(\boldsymbol{n}\times\boldsymbol{H}_{\Omega}\times\nabla\varphi)]{\rm d}\Omega, \end{cases} \tag{1}$$

where Ω represents the boundary of waveguide, $\boldsymbol{n}$ is outside normal vector, k is the wave number of the free space, $\varphi = {\rm e}^{-{\rm j}kr}/r$ is the Green's function of free space, r is the distance between the radiation plane and the observation point.

For region II, due to the exiting aperture, the electromagnetic wave excites diffraction, which affects the current distribution of the aperture. Therefore, the aperture current should be recalculated rather than treating it as a uniform distribution like that in the region I. Within the helical cut, the wave beam is not delivered directly to the free space but after several reflections. Owing to the influence of the scattering effect and diffraction effect, the surface current on each parallelogram is updated at each reflection updated until the wave beam has completely exited the cut. The detailed process of analysis is in the following.

With the propagation of the wave beam from one parallelogram region to another within the helical cut (as shown in Fig. 1(b)), the fields radiated from the parallelogram region will excite a set of extra current sources around the parallelogram region

$$\boldsymbol{J} = 2(\boldsymbol{n}\times\boldsymbol{H}), \tag{2}$$

where $\boldsymbol{H}$ represents the magnetic field radiated from a parallelogram region. The new current source will radiate the new fields

$$\begin{cases} \boldsymbol{E} = \dfrac{1}{2\pi {\rm j}\omega\varepsilon}\displaystyle\int_{\Omega_{\rm II}}[k^2\boldsymbol{J}\varphi + \boldsymbol{J}\cdot\nabla(\nabla\varphi)]{\rm d}\Omega, \\ \boldsymbol{H} = \dfrac{1}{2\pi}\displaystyle\int_{\Omega_{\rm II}}\boldsymbol{J}\times\nabla\varphi{\rm d}\Omega, \end{cases} \tag{3}$$

where $\Omega_{\rm II}$ represents the boundary of parallelogram within region II. The new radiation fields determine a new set of current sources inside of the helical cut. Therefore, the propagation characteristic of the wave beam inside of the cut makes it possible to use an iterative computation to stimulate its current distribution. The initial current distribution on the helical cut could be calculated according to the radiation field from the section I

$$\boldsymbol{J}_0 = 2(\boldsymbol{n}\times\boldsymbol{H}_{\rm I}), \tag{4}$$

where $\boldsymbol{H}_{\rm I}$ is the magnetic field radiated from the region I.

In order to seek the current distribution of the aperture, we could solve the integral equation of the current Stratton–Chu formulation by iteration. Through obtaining current distribution, the radiated fields from the helical cut could be calculated using the current Stratton–Chu formulation. Then, the resultant radiation field computed at the observation point is deduced by

$$\begin{aligned} \boldsymbol{E} &= \boldsymbol{E}_{\rm pI} + \boldsymbol{E}_{\rm p\Pi}, \\ \boldsymbol{H} &= \boldsymbol{H}_{\rm pI} + \boldsymbol{H}_{\rm p\Pi}. \end{aligned} \tag{5}$$

It should be noted that the radiation characteristic of the Vlasov launcher, consisting of a smooth waveguide and a spiral cut, could be analyzed using the proposed method directly in detail since there is only one operating mode.

However, for the Denisov launcher, a mode converter is placed before the helical cut converting the incident rotating TE mode into a mode mixture with a Gaussian beam distribution, the radiation field should be calculated as the superposition of all launching modes. Since the performance of region I is analyzed by using the coupled mode theory, which is applicable to the shallow perturbing waveguide whether highly oversized or not, the proposed method is not restricted to the analysis of these highly oversized waveguides.

3. Numerical calculation and discussion

The computer code based on the proposed method is developed, and the code is used to analyze several launchers that had been reported as the test case. Since it is much more difficult to obtain accurate results for the Vlasov launcher than these for the Denisov launcher because of its significant edge currents, the performance of a $TE_{6,2}$ Vlasov launcher reported in Ref. [17] is initially computed. The diameter of the spiral cut launcher for the test is 4.34 wavelengths with a cut length of seven wavelengths. The contour plot for the calculated x component of the radiated field intensity in the x–z plane, offset eight wavelengths along the y axis, is shown in Fig. 2(a). Figure 2(b) displays the contour plot for the measured x-component of the electric field intensity. It is evident that the measured and calculated field contours are remarkably similar, especially considering the difficulty of performing an accurate measurement, which requires generation of a high-purity $TE_{6,2}$ mode and measurement in the near field zone of the launcher.

The calculated result using the proposed method is considerably closer to the measured result than that obtained from the analytical method which is illustrated in Fig. 2(c). Since the analytical method does not consider the effects of diffraction during the process of calculation, its less accurate results are not surprising. Compared with the result obtained from the MFIE showed in Fig. 2(d), it is difficult to judge whether or not the results calculated with the proposed method are less accurate than those obtained from the measurement. However, one should note that the amount of calculation for the proposed method is less than that of the MFIE since the proposed method just does the iterative calculation within the helical cut rather than solve the integral formulation of Maxwell's equations inside of the whole launcher like the MFIE. The calculations show that the proposed method requires about 77 seconds on a personal computer with a Core 2, 1.83 GHz processor while the MFIE needs 4.5 h and 4 MB of RAM on a 650-MHz Pentium III machine.

Figure 3 illustrates the current changes over the waveguide wall of helical cut during the process of iteration. The uniform distribution is broken gradually, and a non-regular distribution is formed when the convergence condition of calculation is

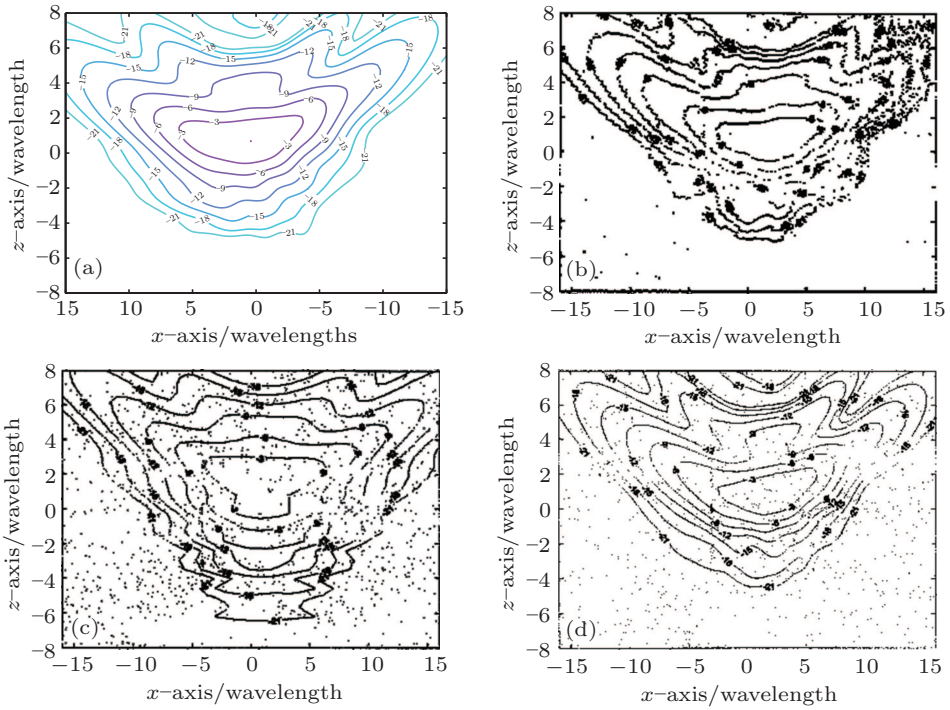


Fig. 2. (color online) The x component of electric field intensity on the x–z plane offset eight wavelengths along the y axis, (a) the result using the proposed method. (b) The measurement result obtained from Ref. [17]. (c) The analytical method result obtained from Ref. [17]. (d) The MFIE calculation obtained from Ref. [17].

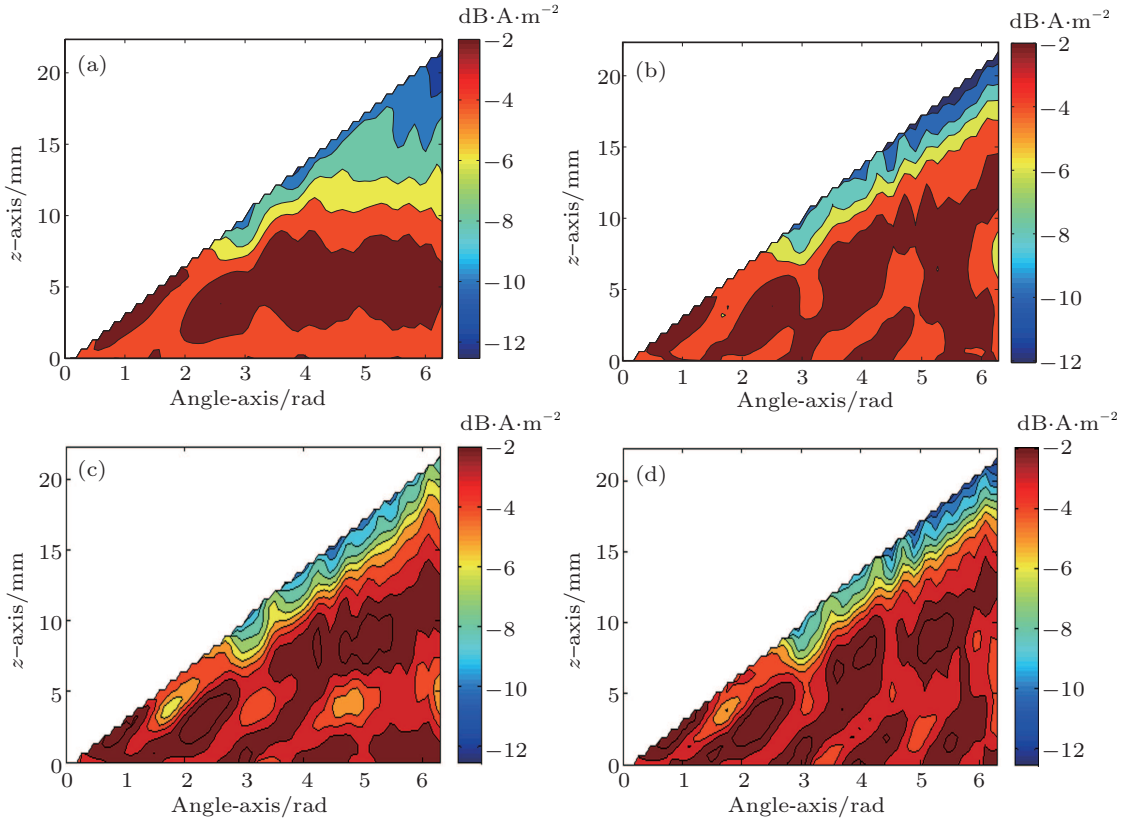


Fig. 3. (color online) The i-iteration solution for the current distribution of the unfolded helical cut: (a) $i = 1$, (b) $i = 3$, (c) $i = 5$, and (d) $i = 7$.

met after seven iterations, which verifies the aforementioned theory analysis that the diffraction will perturb the current distribution of the launcher. Besides, the relatively strong field on the Vlasov launcher's edges of cuts is also demonstrated. The edges of the helical cut could reach the maximum-level fields -2 dB·A·m^{-2} as shown in Fig. 3(d). Such strong fields on the cut edges produce high-diffraction loss.

The radiation field of the 140-GHz $TE_{28,8}$ Denisov launcher studied in Ref. [10] is also investigated using the proposed method. In order to depress the fields at the edges of cuts, the wave beam inside of the launcher is pre-shaped by a dimpled-wall waveguide prior to the spiral cut. The dimpled-wall waveguide is described by the following wall perturbation:[11]

$$R(\phi,z) = a_0 + 0.004z + \delta_1 \cos(\Delta\beta_1 z - \Delta m_1 \phi) + \delta_2 \cos(\Delta\beta_2 z - \Delta m_2 \phi), \quad (6)$$

with a spiral cut length of 54.7 mm, and the helical cut of the launcher is located at 5.027 rad. The radiation is launched from the pre-shaped section by cutting the waveguide wall around one Gaussian bundle, where the wall currents are at a minimum.

The radiated field from the launcher on a plane at the distance of $x = 100$ mm away from the launcher axis is calculated. Figures 4(a) and 4(c) show the results using the proposed method and the low-power measurement of the radiated electrical field distribution from the launcher aperture (the contour map is shown from -30 dB to 0 with the increment of 3 dB), respectively. The calculated field compares very well to the measured field although the peak is shifted slightly from the coordinate center. It is not clear now whether the small differences could be attributed to machining/measurement error or the calculation error. The results obtained from the analytical method,[14] which is shown in Fig. 4(b), show a similar field shift in the peak, which supports the possibility of machining or measurement error. As expected, the analytical method for the Denisov launcher agrees with the measurement significantly better than that for the Vlasov launcher since the aperture current is lowered by the placed mode converter. However, the result of the proposed method is still more consistent with the measurement than that of the analytical method.

The current changes over the waveguide wall of helical cut during the process of calculation are illustrated in Fig. 5. Since a waveguide mode is placed prior to the spiral cut for the Denisov launcher, a nearly Gaussian beam mode is formed at the front of helical cut after the first iteration calculation. A nice Gaussian distribution is formed when the convergence condition of calculation is met after four iterations. Compared with the Vlasov launcher, the edges of the Denisov launcher's cut is nearly zero-level fields. The focused field with a nearly Gaussian beam distribution demonstrates that the Denisov launcher could lower the diffraction loss efficiently and improve the output efficiency significantly.

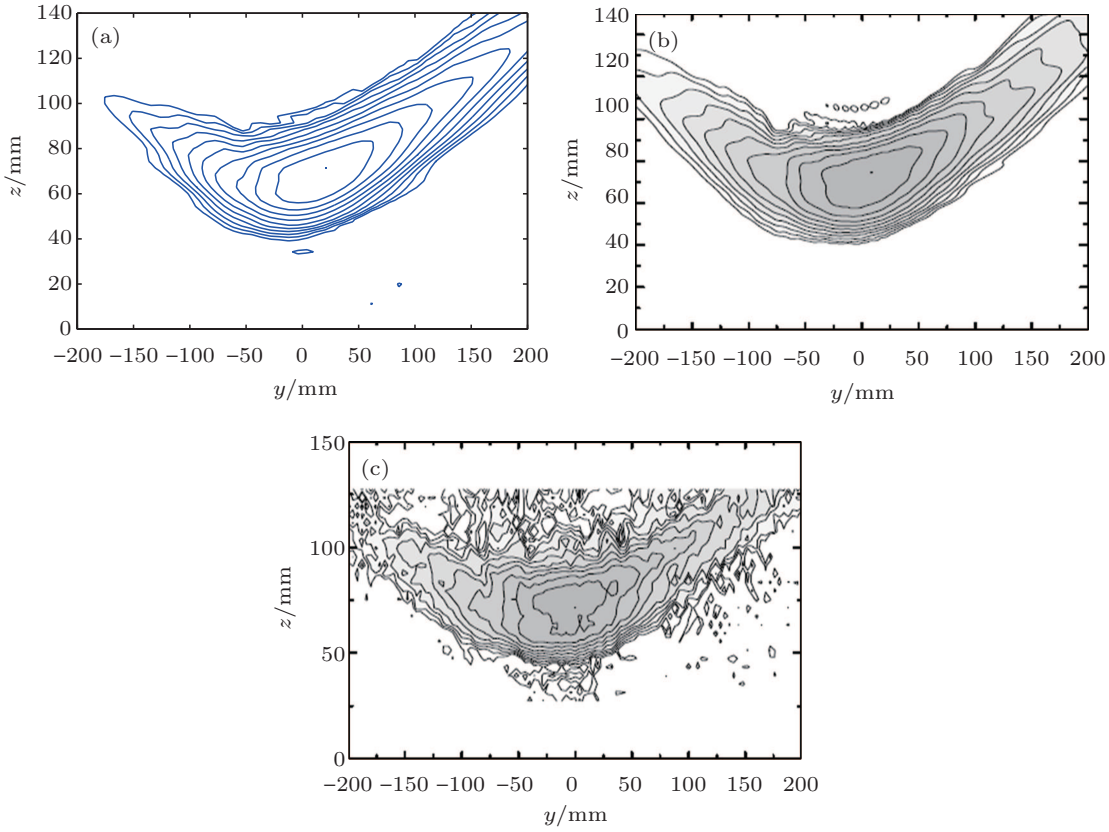


Fig. 4. (color online) The electrical field radiated from the launcher on a plane at the distance of 100-mm axis. (a) The calculation. (b) The analytical method result obtained from Ref. [11]. (c) The cold measurement obtained from Ref. [11].

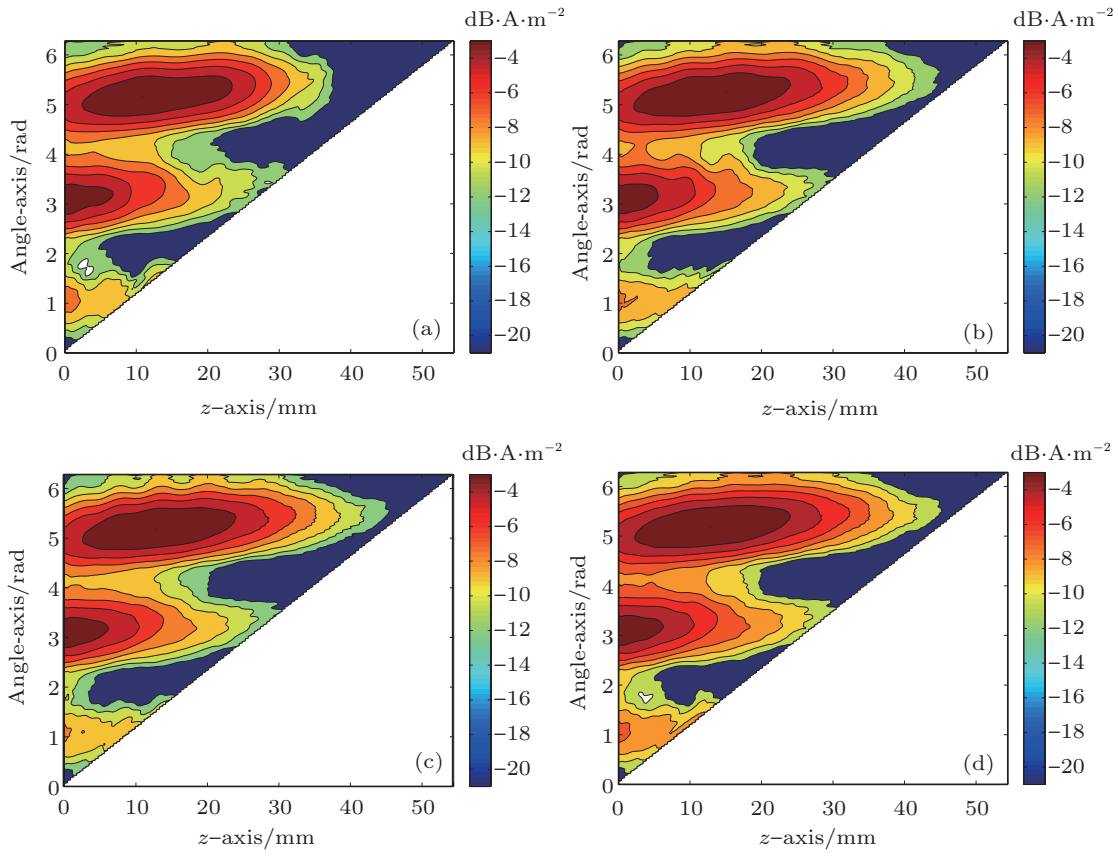


Fig. 5. (color online) The i-iteration solution for the current distribution of the unfolded helical cut: (a) $i = 1$, (b) $i = 2$, (c) $i = 3$, and (d) $i = 4$.

4. Conclusion

A method based on the Stratton–Chu formulation for analyzing the radiation characteristic of the launcher is proposed. Different methods are used to analyze the performance of different regions of the launcher, which make the proposed method apply to a large number of quasi-optical launchers whether highly oversized or not. The feasibility and accuracy of the proposed method has been demonstrated by the close agreement between measurement and calculation. The proposed method provides a fast and accurate alternative to verify the performance of the quasi-optical launcher, and this may be very useful to improve the efficiency of the quasi-optical mode converter, especially for those moderately or weakly oversized launchers.

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