

Pairs of cone–parabola mirrors with chamfers in Cassegrain optical antenna to improve transmission efficiency

XUE CHEN, HUAJUN YANG*, PING JIANG, JINGJING WANG, WEINAN CAIYANG

College of Physical Electronics, University of Electronic Science and Technology of China Sichuan Province 610054, China

The central obstruction of secondary mirror causes a large loss of energy. This paper provides an optimization that a pair of cone-parabola mirrors are added in the Cassegrain optical antenna, which can fully utilize the unused energy. Taking into account of process craft, chamfers are added on the top of the cone and the connection surface between the parabola and the cone of the secondary mirror. A series of optimum structure parameters are analyzed in detail. A main point is that, after considering the reflectivity, transmission efficiency can be improved to 97.27% by our approach. This result demonstrates a better performance than traditional antenna.

(Received August 22, 2016; accepted April 6, 2017)

Keywords: Optical antenna, Chamfers, Cone–parabola mirrors, Transmission efficiency

1. Introduction

Because of the large aperture, no chromatic aberration, and the wide range of available band, Cassegrain antenna is widely used in satellite communication stations and single-pulse radars[1-4] and researchers tend to analyze the transmission performance with optical aberrations or defocus[5-7]. However, serious energy loss caused by secondary mirror obstruction limits the transmission distance. To improve transmission efficiency, lots of optimized antenna designs were proposed in recent years [8-11].

In this paper, a pair of cone-parabola mirrors are added in conventional structure, which can effectively reuse energy obstructed in traditional Cassegrain optical antenna and improve transmission efficiency to 100% theoretically. Besides, considering processing craft, chamfers are added on the top of the cone and the connection surface between the parabola and the cone of the secondary mirror. The design details are proposed and the received spot in our antenna system is displayed. After considering the reflectivity, the transmission efficiency of this optimized antenna with chamfers is 97.27% . Comparing with researches before, results disposed in this paper provide a more practical way to enhance transmission efficiency of optical antenna.

2. Design of antenna system

The structure commonly used is a confocal parabolic system. The beam after collimation has a smaller divergence angle such that the incident light can be approximately regarded as parallel light which is emitted

from a distant point light source. However, the light illuminating on the central zone of secondary mirror will not be reflected to primary mirror and, therefore, can not be transmitted. To make full use of the optical energy, we propose an optimized structure where a cone is added in the center of the secondary mirror of a confocal parabolic system and a cone-shaped torus is added on the edge of the primary mirror. The structure of this antenna system is shown in Fig. 1.

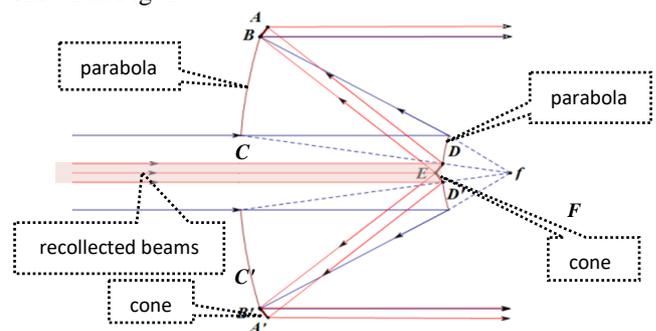


Fig. 1. Schematic diagram of the optimized optical antenna system

As is shown in Fig.1, the primary mirror and a tapered surface intersect at point B while the secondary mirror and a tapered surface intersect at point D. Incident light illuminating on section ED of the secondary mirror will be reflected to section BA of the primary mirror. That's to say, as the secondary mirror suffers from the central reflection, rays (the shaded part in Fig.2) which are lost in traditional Cassegrain antenna will be reflected by the added conic of the secondary mirror and then transmitted by the outer edge cone-shaped reflector of the primary mirror which has the same slope as the cone of secondary

mirror. The two paraboloids share the same focal point so as to achieve parallel output light.

After setting the vertex of the secondary mirror as the origin, the parabolic surface equations of the primary mirror and the secondary mirror in the traditional antenna system are given as follows,

$$y_1^2 = 2p_1(z + d) \quad (1)$$

$$y_2^2 = 2p_2z \quad (2)$$

where d is the distance between the vertex of the secondary mirror and the primary mirror. p_1 and p_2 are twice the value of the focal length of the primary mirror and the secondary mirror, respectively. The effective apertures of them are $2a$ and $2b$, respectively. The corresponding structure parameters of a traditional Cassegrain antenna are listed in Table 1 below.

Table 1. Parameters of the traditional Cassegrain antenna

| $2a$ | p_1 | $2b$ | p_2 | d |
|-------|-------|------|-------|------|
| 150mm | 600m | 30mm | 120m | 240m |
| | m | | m | m |

According to geometrical optics, focus point $F(z_f, y_f)$, point $C(z_c, y_c)$ which can be calculated based on the primary mirror equation and $D(z_d, y_d)$ which is the intersection of the cone and the parabola of the secondary mirror are collinear from Fig.1. Therefore, we have $\lambda FD = DC$ (λ is a nonzero real number) and an equation about y_d is gotten:

$$(z_c - z_d - z_f + \frac{y_d^2}{2p_2})y_d = (\frac{y_d^2}{2p_2} - z_f)y_c + y_f(z_c - z_d) \quad (3)$$

Hence, we can obtain the coordinate of the intersection D which determines the base radius about the cone.

According to the detailed schematic diagram of the ray path as shown in Fig. 2, and combining Snell's law with geometrical optics, we get:

$$k = \tan \beta = \frac{y_d}{z_d - z_e} \quad (4)$$

$$\tan 2\theta = \frac{y_b - y_c}{z_c - z_b} \quad (5)$$

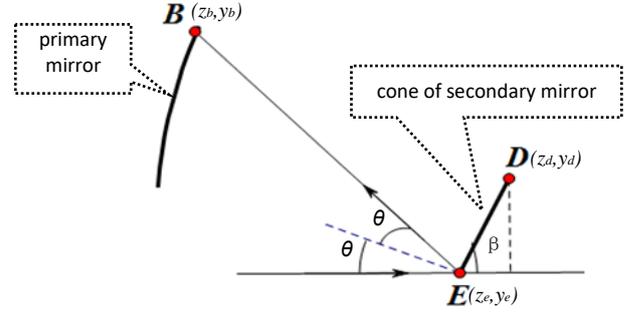


Fig. 2. Detailed schematic diagram of the ray path reflected from the cone of the secondary mirror to the primary mirror

Therefore, the slope and the base radius of the conic parts in the optimized optical system are determined. The detailed data of the elements in the designed optical system are listed in Table 2.

Table 2. Parameters of the cone in our structure

| Curves of conic surface | slope k | base radius (mm) | top radius (mm) | intersection |
|-------------------------|-----------|------------------|-----------------|------------------|
| Secondary mirror | 6.4193 | 3 | 0 | $D(0.038, 3)$ |
| Primary mirror | 6.4193 | 78 | 75 | $B(-235.31, 75)$ |

Based on Table 1 and Table 2, the primary mirror and the secondary mirror of our structure can be determined and are shown in Fig.3. Besides, the received energy distribution of the traditional Cassegrain antenna and the optimized antenna are depicted in Fig.4.

As is shown in Fig.4, it is apparent that a light blue ring appears at the outermost of the energy distribution in Fig.4(b) comparing with Fig.4(a). The same result can be obtained from the two dimensional energy distribution diagram in which two peaks appear on the edge of distribution in Fig. 4(b). That means the incident rays, which are unused in the traditional Cassegrain antenna, are now reused.

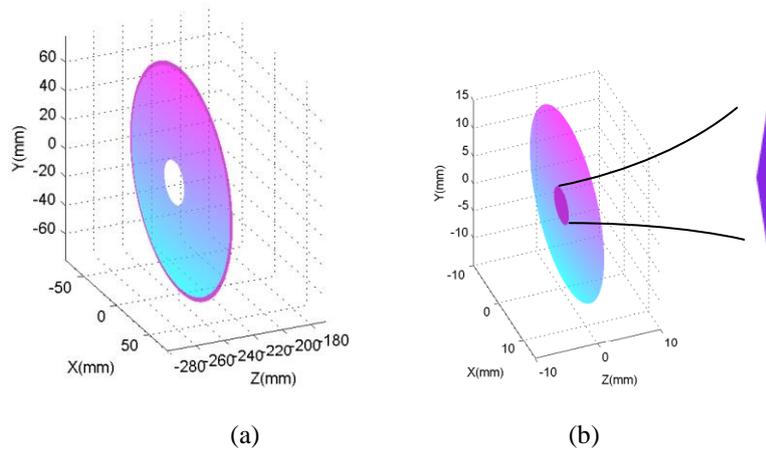


Fig. 3. The primary mirror and the secondary mirror of our structure. The dark purple part represents for the added part comparing with conventional structure. (a) cone-parabola primary mirror (b) cone-parabola secondary mirror

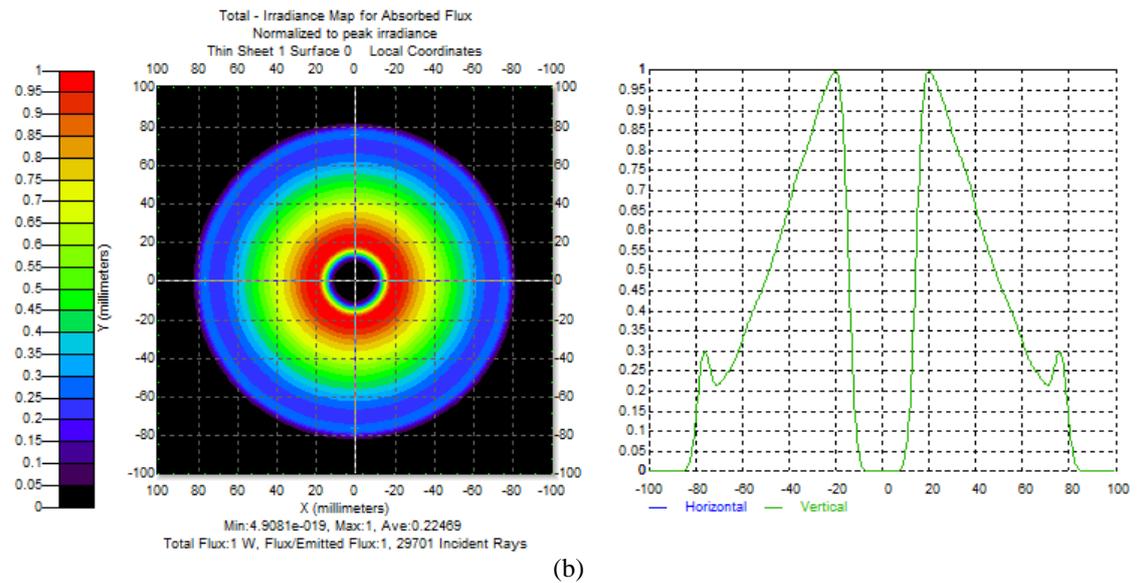
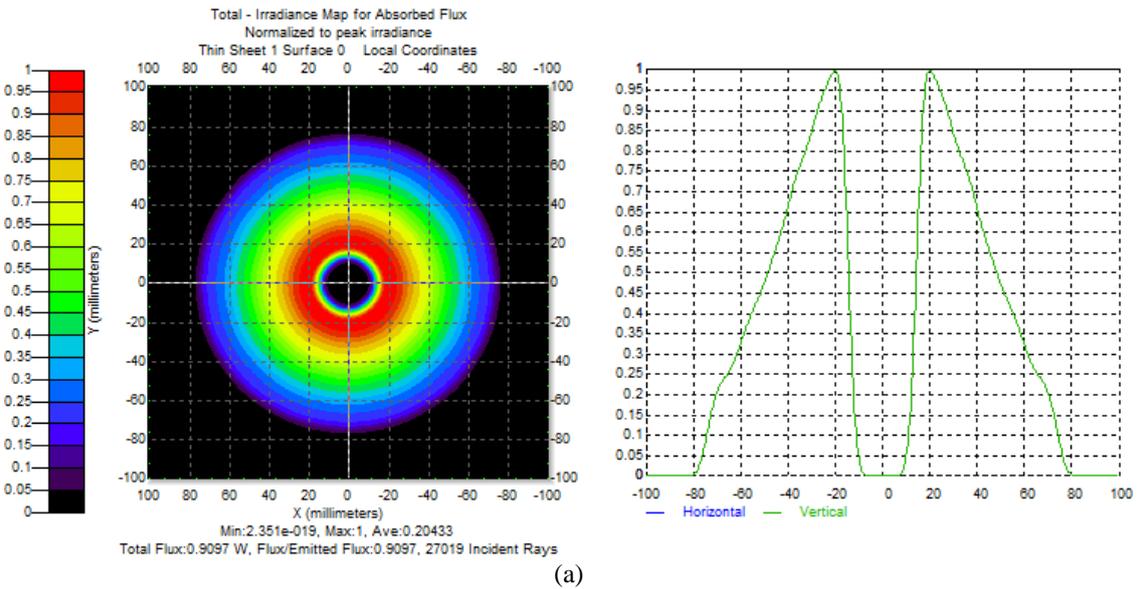


Fig. 4. The received energy distribution: (a) The received energy distribution in the traditional optical system, (b) The received energy distribution in our optical antenna system

3. Add chamfers

When the tapered surfaces are docked with the paraboloid, continuous smooth surfaces cannot be guaranteed and the beam paths are uncertain at the joint surfaces. To solve this problem, chamfers are added to the top of the cone and all the joints so that different components can be connected smoothly.

The profile of the secondary mirror is shown in Fig. 5. In every connective section we make the conical line and parabola tangent with a circle (radius=1mm) and the corresponding pointcuts are N and R. Accurate reconstruction of planar contour mixed with straight lines and arcs is achieved with position or tangent continuity.

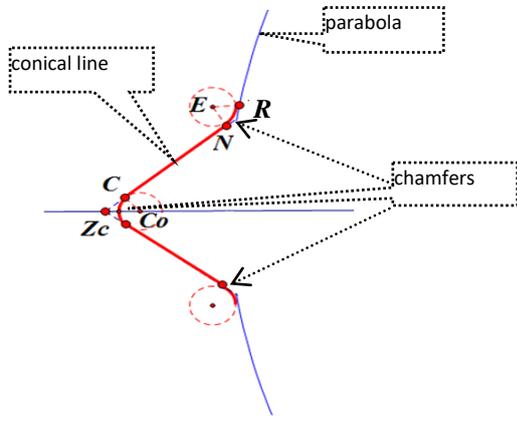


Fig. 5. The profile of the secondary mirror with chamfers

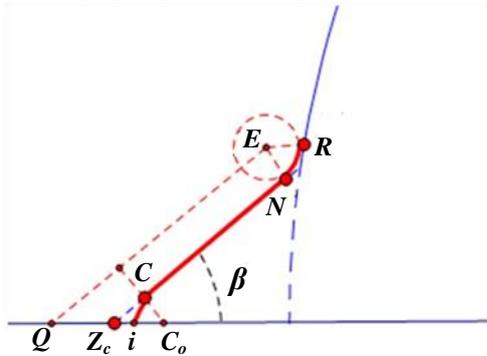


Fig. 6. Schematic geometry of chamfers in the secondary mirror

According to geometry relation shown in Fig.6, equations of the secondary mirror are obtained as follows: segment CN:

$$y = k(z - z_c) \quad (6)$$

circle E:

$$(z - z_e)^2 + (y - y_e)^2 = 1 \quad (7)$$

hence, at E we have:

$$y_e = k(z_e - z_o) = k\left(z_e - z_c + \frac{1}{\sin \beta}\right) \quad (8)$$

Then, by Eq.(2) and Eq.(7), on the basis of common tangent at $R(z_R, y_R)$ we obtain:

$$\frac{z_e - z_R}{y_R - y_e} = \frac{p_2}{y_R} \quad (9)$$

Substituting Eq.(2) and Eq.(8) into Eq.(9), we get:

$$\left(\frac{y_e}{k} + z_c - \frac{1}{\sin \beta} - \frac{y_R^2}{2p_2}\right)y_R = p_2(y_R - y_e) \quad (10)$$

Using Eq.(7) and Eq.(9), we can acquire:

$$(p_2^2 + y_R^2) \left(y_R - \frac{y_R \left(p_2 - z_c + \frac{1}{\sin \beta} \right)}{p_2 + \frac{y_R}{k}} \right)^2 = y_R^2 \quad (11)$$

Finally, combining Eq.(8) with Eq.(11), we have :

$$\left[\left(\frac{p_2}{y_R} \right)^2 + 1 \right] (y_R - y_e) = 1 \quad (12)$$

From Eq.(11), the value of y_R can be calculated. Then we can get all coordinates of the pointcuts (N and R) as well as point $C \left(\cos \beta, z_c + \frac{1}{\sin \beta} - \sin \beta \right)$.

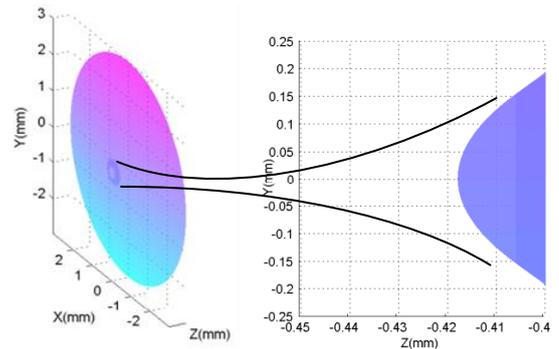


Fig. 7. The vertex angle of the cone with chamfer

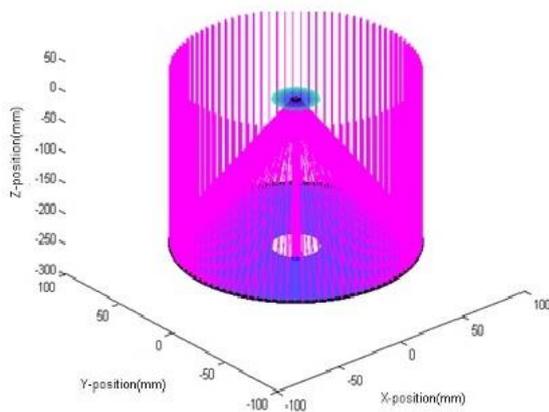
Based on analysis above, Fig. 7 is drawn to show the vertex angle of the cone with chamfer which is conducive to processing craft. The eventual parameters which suit mostly for our design are listed in Table. 3.

Table 3. Parameters of all pointcuts for the secondary mirror

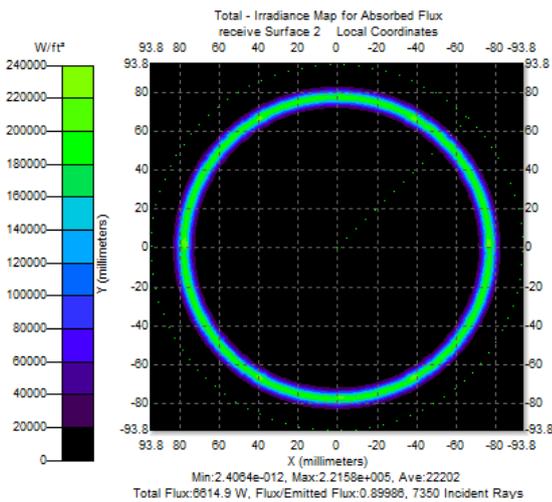
| Coordinates of the pointcuts | C | S | H | R | N |
|------------------------------|---------|-----------|-----------|--------|--------------|
| Z(mm) | -0.4059 | -235.3102 | -235.3144 | 0.0359 | -4.5173e-004 |
| Y(mm) | 0.1539 | 75.0149 | 74.9850 | 2.9347 | 2.7564 |

4. Results and discussion

According to analysis above, we apply an optimization to bringing radiation coming from infinity, which is considered as parallel and then reflected on a given pairs of cone-parabola mirrors, to be parallel finally. All surfaces can be obtained by rotating symmetrically. Based on Snell's law, the complete optical path in the added reflector of the optical antenna system is shown in Fig. 8(a). Furthermore, the reused energy on the primary mirror in our optical antenna system is given in Fig. 8(b).



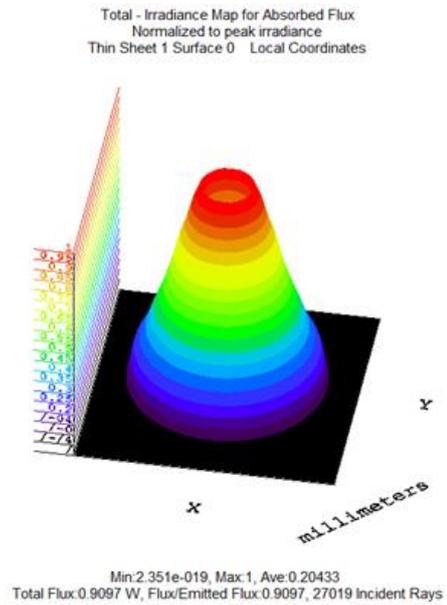
a



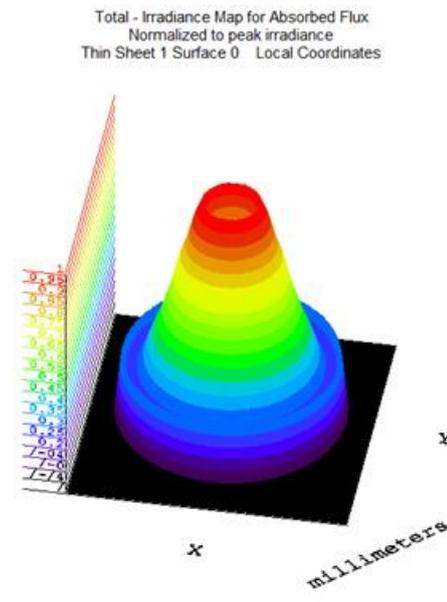
b

Fig. 8. (a) the central beam which illuminates on the cone emits from the antenna. (b) the corresponding received spot of (a) in the optical antenna system

Fig. 8 shows that the incident rays, which are reflected by the cone of the secondary mirror and the conic part of the primary mirror, can be reused in our optimized antenna. The light emitting from the system is parallel as Fig. 8(a) shown.



a



b

Fig. 9. Profiles in the optical antenna system. (a) The spot in the Cassegrain antenna system. (b) The received spot in our optical antenna system

As is shown in Fig. 9(a), energy in the center and the outer circle is increases obviously compared with (b), indicating that structure proposed in this paper can absolutely enhance the transmission efficiency.

The transmission efficiency of the traditional Cassegrain optical antenna in theory is

$$\eta_{old} = \frac{\int_0^{2\pi} d\theta \int_r^a \exp\left(-\frac{2r^2}{\omega_0^2}\right) r dr}{\int_0^{2\pi} d\theta \int_0^a \exp\left(-\frac{2r^2}{\omega_0^2}\right) r dr} = 75.46\% \quad (13)$$

However, the transmission efficiency of our structure in theory is:

$$\eta_{novel} = \frac{\int_0^{2\pi} d\theta \int_{\varepsilon_1}^{\varepsilon_2} \exp\left(-\frac{2r^2}{\omega_0^2}\right) r dr}{\int_0^{2\pi} d\theta \int_0^a \exp\left(-\frac{2r^2}{\omega_0^2}\right) r dr} + \frac{\int_0^{2\pi} d\theta \int_{\varepsilon_3}^a \exp\left(-\frac{2r^2}{\omega_0^2}\right) r dr}{\int_0^{2\pi} d\theta \int_0^a \exp\left(-\frac{2r^2}{\omega_0^2}\right) r dr} = 97.46\% \quad (14)$$

where $\varepsilon_1 = 0.1539$, $\varepsilon_2 = 2.7564$, $\varepsilon_3 = 2.9347$ according to Table.3. For a more practical result, the reflectivity should also be taken into account. Then, the final efficiency of the novel antenna can be calculated as follow:

$$\eta = \eta_{novel} (1-R)^2 \quad (15)$$

After considering different reflectivity according to [12] and [13], the efficiency of the novel antenna under three cases is figured out:

Case 1: $R = 1.00\%$, $\eta = 95.52\%$;

Case 2: $R = 0.50\%$, $\eta = 96.49\%$;

Case 3: $R = 0.10\%$, $\eta = 97.27\%$;

In conclusion, the novel antenna can further increase the transmission efficiency from 75.46% to 97.27%.

5. Conclusions

The characteristics of a two-mirror compound Cassegrain optical antenna have been presented for a distant point source in this paper. The design of the antenna using a cone in the middle of the secondary mirror and adding a cone-shaped torus at the outer edge of the primary mirror offers better efficiency as observed from

simulation. Under an ideal condition, this novel antenna can increase the transmission efficiency to 100%. After considering the chamfers and the reflectivity, the presence of these conic parts which can further increase the transmission efficiency to 97.27% in simulation still results in much higher energy utilization comparing with traditional antenna.

Acknowledgments

Project supported by the National Natural Science Foundation of China (Grant Nos. 11574042 and 61271167), the Young Scientists Fund of the National Natural Science Foundation of China (Grant No. 61307093).

References

- [1] C.-S. Liu, P. D. Lin, *Appl. Opt.* **49**, 126 (2010).
- [2] H. Yang, Y. Hu, C. Li, K. Xie, J. Fu, H. Wei, *IEEE Int. Conf. Commun. Circuits Syst.* **3**, 2016 (2006).
- [3] X. Chu, G. Zhou, *Opt. Express* **15**, 7697 (2007).
- [4] J. Portilla, S. Barbero, *Proc. SPIE* **8550**, 855003 (2012)
- [5] P. Jiang, H. J. Yang, K. Xie, M. Y. Yu, S. Q. Mao, *J. Opt. Soc. Korea* **18**(5), 485 (2014).
- [6] P. Jiang, H. J. Yang, S. Q. Mao, *J. Opt. Express* **23**(20), 26104 (2015).
- [7] M. Y. Yu, H. J. Yang, P. Jiang, Y. Zhuang, L. Chen, S. Q. Mao, *Optik* **127**, 1734 (2016).
- [8] X. J. Ma, H. J. Yang, B. Wang, P. Jiang, M. Y. Yu, Y. C. Huang, S. S. Ke, *Optik* **125**, 1423 (2014).
- [9] L. Zhang, L. Chen, H. J. Yang, P. Jiang, S. Q. Mao, W. N. Caiyang, *J. App. Opt.* **54**(24), 148 (2015)
- [10] M. Y. Yu, P. Jiang, H. J. Yang, Y. C. Huang, X. J. Ma, B. Wang, *Optik* **126**, 795 (2015)
- [11] M. Y. Yu, H. J. Yang, P. Jiang, S. Q. Mao, W. S. He, *Optik* **126**, 2167 (2015).
- [12] Umer Mehmood, Fahad A. Al-Sulaiman, B. S. Yilbas, B. Salhi, S. H. A. Ahmed, *Sol. Energ. Mat. Sol. C.* **157**, 604 (2016).
- [13] T. Uchida, F. Yu, M. Nihei, J. Taniguchi, *Microelectron. Eng.* **153**, 43 (2016).

*Corresponding author: yanghj@uestc.edu.cn