Compound parabolic concentrator applied as receiving antenna in scattering optical communication

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The two-dimensional (2D) compound parabolic concentrator's (CPC) characteristics are analyzed. It is shown that CPC's height is taller and its light collecting ability is stronger with the CPC's field of view decreasing when the bottom radius is unchanged. According to the ZEMAX analysis, CPC is good at collecting optical signal, and the antenna combining CPC with hemispherical lens can gather more optical signal than a single CPC or CPCs combined in series. The light propagation of scattering optical communication based on multiple scattering is simulated by Monte Carlo method, and the results show that using CPC as receiving antenna can strengthen communication system's signal collecting ability and increase its communication distance.

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In free-space ultraviolet (UV) communications, the UV source transmits information through atmospheric scattering. The receiver side usually adopts a receiving antenna to strengthen the signal collecting ability to increase the system's communication distance because of the strong effect of atmospheric attenuation on optical signal[1−5]. Usually, we use paraboloid antenna as the receiving antenna. Compound parabolic concentrator (CPC) is a non-imaging concentrator based on marginal optical principle. It is used as a radiation detector in high-energy physics. Because all of the rays in the range of receiving angles could be connected to the detector, it was widely used for concentrating solar radiation in the 70s of the last century. In this letter, we analyze the CPC's structure and its optical characteristics. We propose to use the CPC in scattering optical communication as a receiving antenna since it can gather feeble signals and increase communication distance.

The CPC's focus is set in different positions when it is combined with different detectors. There are four kinds in usual: flat, upright, triangle, and tube[6]. In this letter, the structures and traits of flat CPC are discussed.

The generatrix of CPC is composed of a section of parabola and a straight (see Fig. 1). The CPC's profile curve equation is

$$\begin{aligned}&(x\cos\theta_0+y\sin\theta_0)^2+2b(1+\sin\theta_0)^2x\\&\quad-2b\cos\theta_0(2+\sin\theta_0)y\\&\quad-b^2(1+\sin\theta_0)(3+\sin\theta_0)=0,\end{aligned}\qquad(1)$$

where θ_0 is the nip angle of axis |FP| and CPC's symmetrical axis oy, and b is CPC's bottom radius. According to Eq. (1), we know that flat CPC's structure is determined only by θ_0 and b.

Gain is an important parameter which reflects CPC's light-gathering ability. According to the maximum gain condition[7]: $\mathrm{d}x/\mathrm{d}y$=0, we obtain

$$a_{\max}(\theta_0)=x_{\max}=b/\sin\theta_0,\qquad(2)$$

$$h_{\max}(\theta_0)=y_{\max}=b(1+\csc\theta_0)/\tan\theta_0,\qquad(3)$$

where $a_{\max}$ is the maximum of CPC's receiving aperture radius and $h_{\max}$ is the maximum of CPC's height. According to the definition of the gain, we obtain the maximum two-dimensional (2D) gain as

$$c_{\max}(\theta_0)=a_{\max}(\theta_0)/b=1/\sin\theta_0.\qquad(4)$$

Assuming that CPC's bottom radius b is 1 cm, when θ_0 is 5°, c approximates 11.47 and h approximates 143 cm; when θ_0 is 15°, c approximates 3.86 and h approximates 18 cm; when θ_0 is 30°, c approximates 2 and h approximates 5 cm. The CPC has a high gain and it will be higher as θ_0 is smaller. Figure 2 shows the three-dimensional (3D) CPCs with different θ_0 values. The receiving aperture radius, height, and gain of CPC vary indirectly with the change of θ_0.

Figure 3 shows the ray-tracing results of CPC's cross section. Rays whose incident angles are in the range of $\{\theta\,|-\theta_0<\theta<\theta_0\}$ are reflected and arrive at the CPC's bottom. According to the results of ray-tracing, rays whose incident angles are within the receiving range would be reflected to the bottom and the gain is $c_{\max}$. So, the angle θ_0 is CPC's field of view.

Intercept ratio is defined as $k=h/h_{\max}$ ($h\le h_{\max}$).

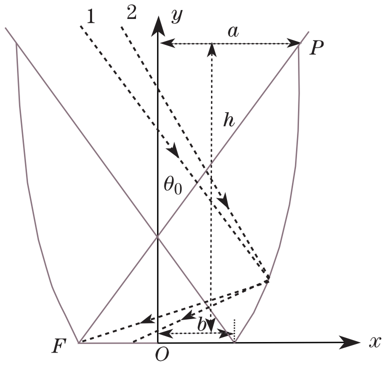

Fig. 1. Sketch of CPC.

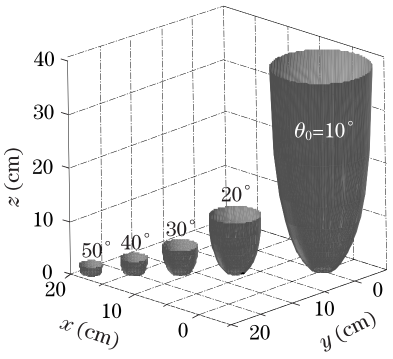

Fig. 2. 3D-CPC with different θ_0 values (b=1 cm).

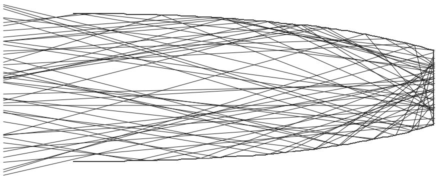

Fig. 3. Ray-tracing result of CPC (θ_0=30°).

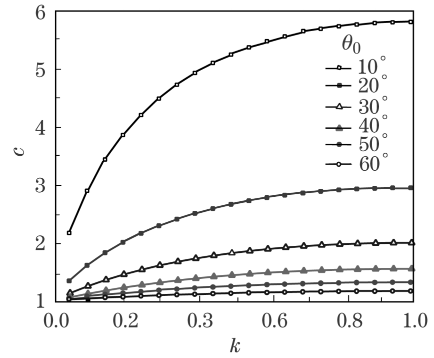

Fig. 4. Relationship between c and k.

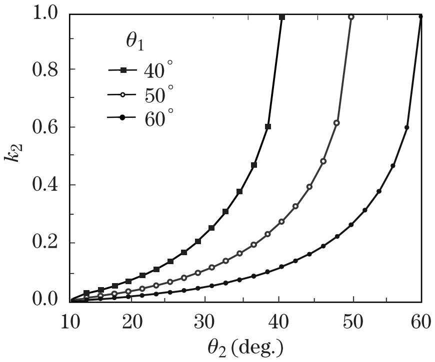

Fig. 5. Intercept ratio.

Then Eq. (4) is equivalently written as

$$c(\theta_0,k)=\left\{-(1+\sin\theta_0)[\sin\theta_0+k(1-\sin\theta_0)] + 2\sqrt{k\cos^2\theta_0+\sin^2\theta_0}\right\}\Big/ [(1-\sin\theta_0)\sin\theta_0]. \quad (5)$$

It is clear that c is related to k by observing Eq. (5). In detail, c directly varies as k changes, and the faster c increases, the larger the value of k is; if the value of θ_0 is relatively small, c is influenced significantly by k; when the value of θ_0 is larger, k affects c slightly (see Fig. 4).

On the assumption that CPC$_1$ and CPC$_2$ have the same bottom radius and their fields of view are θ_1, θ_2 ($\theta_1 > \theta_2$), we get $h_{\max}(\theta_1) < h_{\max}(\theta_2)$ and $c_{\max}(\theta_1) < c_{\max}(\theta_2)$. We assume that

$$c(\theta_2,k_2)=c_{\max}(\theta_1,1), \quad (6)$$

and then we get

$$k_2=\left\{2-\sin\theta_2[1+\sin\theta_2+(1-\sin\theta_2)/\sin\theta_1] - 2\sqrt{(1-\sin\theta_2)(1-\sin\theta_2/\sin\theta_1)}\right\}\Big/\cos^2\theta_2. \quad (7)$$

Figure 5 shows CPC$_2$'s intercept ratio curve under the conditions that CPC$_1$ and CPC$_2$ have the same gain and bottom radius when the CPC$_1$'s fields of view are 40°, 50°, and 60°, respectively. It is indicated that when CPC$_1$ and CPC$_2$ have the same height, CPC$_2$'s light-gathering ability is stronger; when CPC$_1$ and CPC$_2$ have the same gain, CPC$_2$'s height is lower.

We can draw a conclusion that CPC owns large field of view and strong light-gathering ability. Thus we can design a needed CPC with given b and θ_0. When the bottom radius is given, the height and gain increase as the field of view decreases. We should choose the value of k (usually 0.5–0.8) properly, and then we can reduce the CPC's height to advance the machining and employment without influencing the light-gathering ability markedly.

We simulated the 3D-CPC's light collecting ability by using ZEMAX when we chose a circular diffuse cosine source to simulate the distribution of optical signal after the atmospheric scattering. The source's rays emit in a cosine distribution of the form

$$I(\theta)=I_0(\cos\theta)^{C_n}. \quad (8)$$

The larger C_n is, the narrower the distribution becomes. On the assumption that we set the parameters of the source like Table 1, and ignore the energy loss resulting

Table 1. Parameters of the Source

Analysis Rays	Power (W)	Cosine Exponent	x Half Width(cm)	y Half Width(cm)
10^5	1	2	4	4

Table 2. Detector's Incoherent Irradiance

	Size (cm)	Peak Irradiance (W/cm^2)	Total Power (W)
Fig. 6	4×4	0.031	0.045
Fig. 7(a)	4×4	0.094	0.314
Fig. 7(b)	4×4	0.131	0.420
Fig. 7(c)	2×2	0.175	0.071
Fig. 7(d)	2×2	0.150	0.081

from the CPC's reflection and the hemispherical lens' absorption, we obtain the results shown in Table 2, Figs. 6 and 7 which are calculated by ZEMAX's Monte Carlo ray-tracing method.

Figure 6 shows the detector image of the incoherent irradiance without antenna. Figure 7 shows the detector image of the incoherent irradiance using different CPCs as its antennas. Total powers in Table 2 show that using CPC as an antenna could be good for collecting the optical signal. The antenna combining CPC with hemispherical lens can gather optical signal more efficiently than a single CPC, which is equivalent to augmenting the antenna's receiving caliber when the size of detector is fixed (see Figs. 7(a) and (b))[8]. But the hemispherical lens should be designed appropriately, since it is difficult to machine and its larger size will lead to more absorption loss of energy. Figures 7(c) and (d) show that it could not strengthen the light collecting ability by combining CPCs in series. Though the antenna's receiving caliber is bigger, part of the incident rays of the front CPC cannot arrive at the bottom of the latter one when the detectors' sizes are the same.

Scattering optical communication uses atmospheric scattering as its channel and optical signals will attenuate acutely by scattering and absorption of atmosphere which limits the communication system's corresponding range. Simultaneously, optical signals will distribute in the whole sky by the scattering. So we need a reflection antenna with large field of view and high gain, and CPC satisfies these requirements.

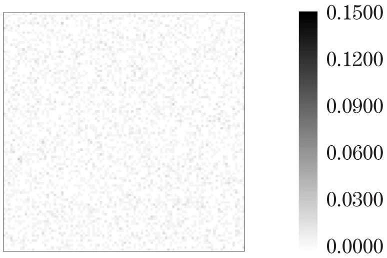

Fig. 6. Detector image of the incoherent irradiance with no antenna. The distance between source and detector is 12 cm.

We simulated the propagation of optical signals with Monte Carlo method[9−11]. We got the received signals' statistical information of flying time and detectable weight by tracing the generation, collision, and disappearance of large mount of photos (about 10^8).

On the assumption that CPC's field of view is 20° and its bottom radius is 1 cm, we simulated the propagation under a given condition (the detecting distance is 500 m and the stadia is 23 km) by Monte Carlo method. If the emission energy of optical pulse is 1 J, the signals' energy arriving at the detector will be about 3.25 nJ using no antennas and 11.20 nJ using CPC as the receiving antenna, respectively. Figure 8 shows the results in the form of pulse response curves from which we know that using CPC can strengthen the system's signal-gathering ability.

We manufactured a CPC by numerical control machine. Then we deposited an aluminum film on the CPC's inner surface by thermal evaporation coating. Its receiving angle was 30° and bottom radius was 3 cm. To validate the CPC antenna's validity, we used low-pressure mercury lamp as light source and set the communication distance as 40 m. What's more, an obstacle (height: 1.5 m, width: 1 m, thickness: 0.5 m) kept out the direct light from the source to the receiver which was mainly composed of CPC, filter, and photomultiplier tube (PMT).

Table 3 shows the receiver's outputs with and without using CPC as antenna at different receiving angles. The CPC antenna's gain is about 1.8, which is far from the theoretical value 4. The reasons are given below. 1) Because the process level is relatively low and the surface roughness of CPC is not ideal, rays cannot propagate ideally to the focal plane (CPC's bottom). 2) The degree of vacuum is not high and the CPC's surface is not clean enough during the coating process, which causes the density of CPC's films being not high. So the light might not propagate ideally to the focal plane. 3) The CPC's bottom radius is 3 cm and the filter's radius is 1 cm, so the CPC cannot tightly combine with the filter subsequently connecting with PMT. So a part of light energy dissipates.

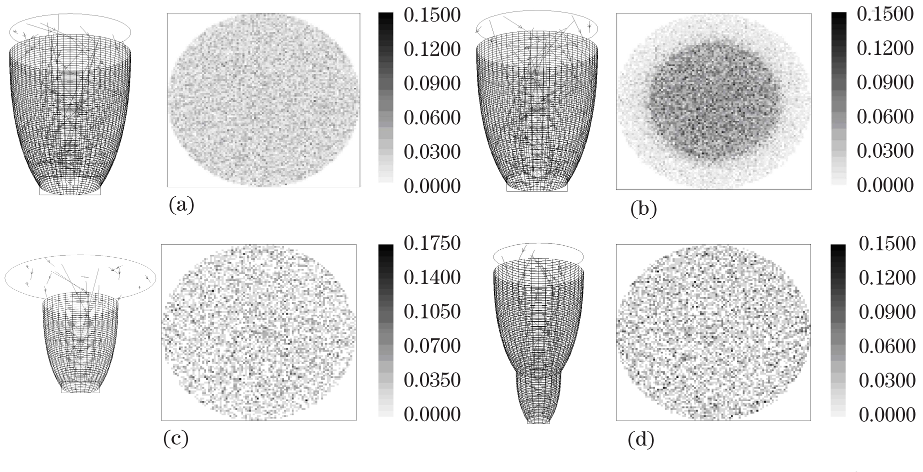

Fig. 7. Detector images of the incoherent irradiance with CPC as its antenna. (a) b=2 cm, θ_0=30°, h=10.4 cm; (b) b=2 cm, θ_0=30°, h=10.4 cm, radius of hemispheric lens R=2 cm; (c) b=1 cm, θ_0=30°, h=5.2 cm; (d) two CPCs in series, CPC$_1$: b=2 cm, θ_0=30°, h=10.4 cm; CPC$_2$: b=1 cm, θ_0=30°, h=5.2 cm. The distance from the light source to the upper surface of the CPC is 1.6 cm.

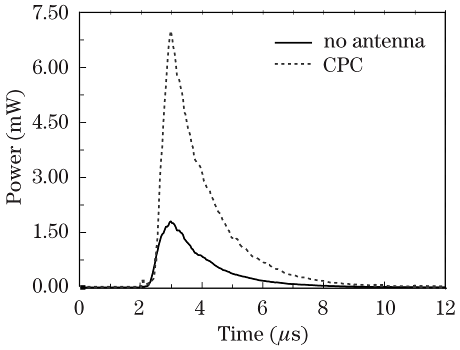

Fig. 8. Pulse response curve.

Table 3. Measurement Results

Receiving Angle (deg.)	V_1 (mV)	V_2 (mV)	Gain (V_2/V_1)
0	102	166	1.63
10	109	186	1.71
20	113	202	1.79
30	119	219	1.84
40	124	233	1.88
50	130	253	1.95

V_1 is the result without using antenna, V_2 is the result using CPC antenna.

In conclusion, we discuss the CPC used as a receiving antenna in atmosphere scattering optical communication. CPC's structure is merely determined by θ_0 and b, and light within the field of view would be absolutely reflected to the bottom aperture. CPC has the traits of large field of view and high gain. CPC employed as a receiving antenna in scattering optical communication can efficiently increase the corresponding range. In the next step, we will enhance the process level of CPC and do some experiments.

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