Double reflector configuration for optimal exposure of wideband focal plane arrays with optical beamforming

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Double Reflector Configuration for Optimal Exposure of Wideband Focal Plane Arrays with Optical Beamforming


Abstract—An optimized double-reflector antenna concept for a wideband focal plane array (FPA) configuration is presented for Ka-band applications with a limited scan range, e.g. ground terminals for satellite communication. The proposed reflector configuration allows to maximize the number of active array elements and minimize the actual array size during scanning. In addition, the FPA configuration has been optimized for wideband optical true-time-delay (TTD) beamforming, resulting in wideband operation from 20-40 GHz. Based on a minimum required 80 % aperture efficiency at 30 GHz, the double-reflector concept allows expanding the illuminated region of the array by a factor of 60 as compared to traditional prime-focus configurations. The proposed configuration also decreases the magnification factor $M$ by a factor of 2.5, as compared to the double-parabolic configuration for a $\pm 1.5^\circ$ scan range.

Index Terms—Reflector antennas, antenna array, wideband arrays, optical arrays, antenna simulation.

I. INTRODUCTION

In the past decades, focal-plane arrays (FPAs) have become an interesting alternative to conventional horn-fed reflector antennas in a number of applications, e.g. in radio astronomy [1] and in Ka-band satellite communication [2]. However, the small number of simultaneously active array elements is representing a serious limiting factor for this technology, in terms of number of multiple beams or scan range [3] and level of achievable effective isotropic radiated power (EIRP) [4]. A low EIRP level limits the use of low-cost silicon integrated circuits. In addition, it is a challenge to provide a proper exposure of the FPA even for relative small scan angles of the main beam, due to the significant beam deviation in the focal plane (see Fig. 1) [5]. Therefore, it is necessary to investigate various reflector configurations in order to improve the FPA illumination and increase the number of simultaneously active elements, during beam scanning over a wide instantaneous bandwidth.

This paper presents the outcome of a study to overcome these limitations. Our goal was to develop a wideband FPA system, operating in the frequency band 20-40 GHz. The beamforming of the array elements is done with a novel optical beamforming network, resulting in multi-beam operation over a wide instantaneous bandwidth [6]. The optical beamformer utilizes true time delay (TTD), implemented in optical integrated circuits (ICs). These optical ICs generate frequency-independent time delays (linear phase) [7], therefore alleviating the beam-squinting problem prevalent in wideband beamformers. A dispersive optical TTD device generates wavelength-dependent time delays, thus can be used to generate simultaneous multiple beams by using light sources of different wavelengths. In addition, TTD includes immunity to electromagnetic interference (EMI), scalability and low weight thanks to the high level of photonic integration of the optical beamformer circuits. A linear phase distribution along the array elements of the FPA is an important requirement for the realization of a compact TTD optical beamformer circuit [8]. Therefore, our antenna design targets a linear phase distribution along the array elements of the FPA.

Another important requirement for our FPA system is related to the scan range. We have investigated two specific scan ranges: $\pm 1.5^\circ$ and $\pm 3^\circ$ for 2-dimensional scanning, which is much more challenging than 1-dimensional scanning. These are typical values for reflector installation and calibration in Ka-band, in two-way satellite communication [9] and in surveys for radio astronomy [10], respectively. In conventional FPA systems the array is not used very efficiently, even in the case of a limited scan range. The number of simultaneously illuminated array elements is limited, due to the small region of high power density in the focal plane. In addition, the required size of the array is quite large, due to the significant spot beam deviation from the array center during scanning. As a consequence, the number of simultaneous active elements is small as compared to the total number of array elements.

Therefore, the achieved EIRP levels, as well as the scan performance, are limited [4]. In summary, we have the following requirements for the FPA system:

- wide band in the range of 20-40 GHz,
- linear phase distribution in the focal region,
- wide illumination area of the array to maximize the EIRP,
- decrease beam deviation in focal plane region during scanning.

In this paper, we will optimize the FPA system for these requirements. For that purpose, we will investigate and compare three configurations: i) a classical prime-focus reflector, ii) a double parabolic configuration and iii) our...
proposed optimized FPA configuration. We will use a classical prime focus reflector with \( F/D = 0.6 \) and \( D = 0.8 \) m. The array element spacing is chosen as \( \lambda_0/2 \) at 40 GHz, where \( \lambda_0 \) is the free-space wavelength. All simulations have been performed with GRASP [11].

II. ILLUMINATION LIMITATIONS OF CLASSICAL PRIME-FOCUS FPAS

For large \( F/D \) ratio’s and small scan angles, when neglecting the spill-over and decoupling efficiencies, the co-polar component of the electric field distribution in the focal plane of a prime-focus reflector can be approximated by:

\[
E(r) = \frac{2 J_1(k r \sin(\Psi_0))}{k r \sin(\Psi_0)}
\]

where \( J_1 \) is the Bessel function of the first kind with order 1, \( \Psi_0 = \pi/4 \) is the subtended angle of the reflector, \( k \) is the wavenumber and \( r \) is the distance from the center of the focal plane or aperture radius, see also Fig. 1 and [12].

According to (1), it is clear that the same reflector operating at higher frequencies will illuminate a smaller region in the focal plane. As an example, the electric field in the focal plane for a classical prime focus reflector is presented in Fig. 2. The normalized power density distribution of the electric field, calculated according to (1), is shown in Fig. 3. By integrating the electric field on the focal plane and normalizing it to the total power \( P_{tot} \) received by the reflector and free space impedance \( Z_0 \), it is possible to calculate the aperture efficiency \( \eta(r) \) in the focal plane (see Fig. 1) [5], which is presented in Fig. 4:

\[
\eta(r) = \frac{1}{P_{tot}} \int_0^{2\pi} \int_0^r \frac{[E(r')]^2}{2\pi} r' dr' d\phi
\]

For the considered FPA system employing a wideband optical beamforming network, it is required to have a linear phase distribution along the array elements. The phase distribution in the focal plane of the investigated parabolic reflector is shown in Fig. 5 as well as an example of an optimal phase-distribution in order of the optical beamformer to be used. It is clear that the phase distribution is far from linear along the aperture radius at a single frequency. If we consider the aperture area at 30 GHz for which the normalized power density is above -3 dB (see Fig 3), the linearity of the phase distribution shows a root-mean-square (rms) error of 6.36°. This will deteriorate the overall performance of our FPA system with optical beamforming [13].
The aperture efficiency and field distribution cuts for different scan angles of the main beam are presented in Fig. 6. We can observe that for various scan angles of the main beam, the region of maximum power will have almost the same size, but will be shifted away from the array center. This means that the array size should be increased in order to provide scanning capabilities. However, the number of simultaneously active elements will remain the same.

Figure 6. Aperture efficiency and electric field cuts in the focal plane for different scan angles of a classical prime focus reflector with $F/D = 0.6, f = 30$ GHz.

III. DOUBLE PARABOLIC REFLECTOR CONFIGURATION

Double parabolic reflector configurations are commonly known as imaging reflector systems [14]. They are constituted by a feeding phased array properly magnified by two reflector antennas. Such systems efficiently combine the advantages of reflector and array antennas. They are commonly used to generate reconfigurable beams over a small angular scan range. Some sort of beam compression is realized to increase the illuminated region of the array significantly and, as a consequence, the number of simultaneously active elements. The working principle of a double parabolic reflector and the relevant geometrical dimensions are schematically shown in Fig. 7.

Figure 7. Symmetrical double parabolic reflector configuration.

The simulated electric field distribution in the array plane for a double parabolic reflector configuration with $F_m/D_m = 0.6$ and $F_m/F_s = 8$ is shown in Fig. 8. The corresponding aperture efficiency is shown in Fig. 9. The size of the sub-reflector was chosen based on the array size from section II for the scanning case of $\pm 3^\circ$ and aperture efficiency of 95%, $D_m/D_s = 4.5$ (see Fig. 6). The same excitation mechanism has been used. A planar array has been located at the surface of the main reflector. The sub-reflector blockage was included in the simulation. The resulting phase distribution in the array plane is presented in Fig. 10.

According to Fig. 8 and 9, the illuminated region in the array plane is significantly expanded as compared to the classical prime-focus system. Based on an aperture efficiency of 80%, the illuminated area of the array has been increased by a factor of 150, for this particular example. The aperture efficiency curve is less steep than in the case of a prime focus reflector, which indicates a broadening of the focal field distribution. In addition, the phase relation between the array elements shows an inverted V-kind of distribution as a function of $r$ for reasonable array sizes over the entire frequency range, with a linearity error of 3.06 at 30 GHz.

The aperture efficiency and electric field cuts for different scan angles are presented in Fig. 11. The required array size in case of scanning should be significantly increased in order to achieve sufficient aperture efficiency. The poor performance is due to the amplification of the incidence angle on the array surface, expressed by the magnification factor $M$ [15]:

$$\theta = \frac{F_m}{F_s} \theta = M \theta$$

(3)

where $\theta$ is the angle of incidence of the incident field, $\theta_0$ is the incident angle on the array surface (Fig. 7). As a result, even a small beam deviation of the incident wave causes a significant shift of the irradiated region. As a consequence, the array size should be significantly increased. Therefore, the number of active elements will be still significantly less than the number of inactive array elements. Therefore, also with this
configuration an effective exposure of the FPA cannot be achieved.

**Figure 10.** Phase distribution in the array plane of a symmetrical double parabolic reflector, $F_m/D_m = 0.6$ for main reflector, $F_m/F_s = 8$ for sub-reflector.

**Figure 11.** Aperture efficiency and electric field cuts in the array plane for different angle of incidence of the incident field of a symmetrical double parabolic reflector, $F_m/D_m = 0.6$ for main reflector, $F_m/F_s = 8$ for sub-reflector, $f = 30$ GHz.

**IV. OPTIMIZATION OF DOUBLE REFLECTOR CONFIGURATION FOR FPA**

Classical prime-focus reflector antennas have a relative small illuminated region in the focal plane and do not allow to fully use the FPA capabilities. A double parabolic reflector allows increasing significantly the number of simultaneously active elements in the FPA system and can improve the linearity of the phase relation between the array elements. However, there is still the issue of the magnification of the incident angle on the projected FPA surface. Therefore, we need to find a way to decrease the magnification factor and to keep a sufficient number of active elements, at the same time. In order to do that, we have optimized the ratio between the required aperture radius for a $1.5^\circ$ scan angle versus $0^\circ$ scan angle ($AR_{1.5}$) and the ratio between a scan angle of $3^\circ$ versus $0^\circ$ scan angle ($AR_3$).

As a starting point, a Cassegrain ring-focus configuration has been chosen [16]. In these systems, the electromagnetic field is focused in a single feed point located in the plane of the main reflector (see Fig. 12 (a)). It is possible to shift the feed away from the sub-reflector and, at the same time, keep all beams focused on the feed, by optimization of the sub-reflector shape [17]. In this way the beam can be broadened in the main reflector plane, where the array will actually be placed. If the illumination cone of the second reflector has a focus on infinity (Fig. 12 (b)), the configuration could be considered as a double parabolic reflector of section III.

The field distribution in the array plane has been determined for a number of cases in which the focal point is shifted away from the original feed plane. The FPA is located at the surface of the main reflector (see Fig. 12 (c)). The size of the sub-reflector has been defined in the same way as for the double parabolic configurations of section III. The aperture efficiency has been calculated based on the electric field distribution according Eq. (2). The required aperture radius, corresponding to an $80\%$ aperture efficiency at $30$ GHz, is presented in Fig. 13 for angles of incidence of $1.5^\circ$ and $3^\circ$. Wider scanning (e.g. $5^\circ$ and $10^\circ$) is an issue, due to the necessity of a larger sub-reflector resulting in significant blockage [18]. Note that blockage of the sub-reflector is included in our model.

**Figure 12.** (a) Ring focus dual reflector (b) ring focus dual reflector with single shifted feed (c) ring focus dual reflector with FPA.

**Figure 13.** Aperture radius versus scan angle based on $80\%$ aperture efficiency for a ring focus dual reflector with FPA, $f = 30$ GHz , blockage of sub-reflector is included.

From Fig. 13, we can conclude that the aperture radius is increasing with increasing shift from the feed plane (Ls) for all considered scan angles. However, for the case of non-zero incidence ($1.5^\circ$ and $3^\circ$), the required aperture radius grows faster than for normal incidence. In order to find the optimum, the ratios $AR_{1.5}$ and $AR_3$ are presented in Fig. 14. It appears that these ratios can be optimized as a function of $L_s$ (see Fig. 12 (b)). According to Fig. 14, the minimum value of $AR_{1.5}$ is $1.54$ and the minimum of $AR_3$ is $2.22$. For the classical prime focus reflector case, according to Fig. 6, we find that $AR_{1.5}=2.94$ and $AR_3=5.87$. For the double parabolic reflector configuration, according to Fig. 11, we find that $AR_{1.5}=2.06$ and $AR_3=3.43$. 


Therefore, the proposed configuration is optimal in terms that we minimized the ratio between the required aperture radius for a $1.5^\circ$ scan angle versus $0^\circ$ ($AR_{1.5}$) and the ratio between a scan angle of $3^\circ$ versus $0^\circ$ ($AR_3$).

The optimization for both scan angles at the same time is not possible. Each value of $L_s$ produces a different shape of the sub-reflector with different eccentricity. In our case, the optimal value of $L_s$ for both cases quite similar. Therefore we have been used $L_s = 0.22$ m as the optimal configuration. In this case the ratio between the main reflector and the sub-reflector is $D_m/D_s = 8$, $F_m/D_m = 0.6$ and $F_s/D_s = 6.9$. The position of the sub-reflector has been chosen in such a way that we obtain an aperture efficiency level of 95 % on the sub-reflector surface for the scanning case of $\pm 3^\circ$.

![Figure 14. Ratios between aperture radius for different angle of incidence of the incident field based on 80 % aperture efficiency for a ring focus dual reflector with FPA, $f = 30$ GHz , blockage of sub-reflector is included.](image)

The calculated field distribution in the array plane for the non-scanning case of the optimized symmetrical double reflector is presented in Fig. 15, the corresponding aperture efficiency in Fig. 16. The phase distribution in the array plane is presented in Fig. 17 (a). The blockage of the sub-reflector is included in all these results. According to Fig. 15 and 16, the illuminated region in the array plane is significantly expanded as compared to the classical prime focus reflector in section II. The illuminated area of the array has been increased by a factor of 60 based on an aperture efficiency of 80 %. The phase distribution between the array elements has approximately a linear V-kind of shape within the array size with rms error of 1.65%. For the central array element ($r = 0$), the phase dependence versus frequency is very linear (rms error does not exceed 1 % at 30 GHz for all considered reflector configurations), see Fig. 17 (b). Therefore, this configuration is more suitable for the optical beamforming network. Fig. 17 (c) presents the phase distribution for the optical beamforming, which operates in a band 20-40 GHz, with discretization along frequency 1 GHz and $\lambda/2$ distance between array elements, at the highest frequency. Fig. 17 (d) presents the phase distribution in the array plane at 30 GHz for all investigated reflector configurations.

![Figure 15. (a) Field distribution of an optimized symmetrical double reflector antenna (b) 2D illustration of pattern in the array plane of an optimized symmetrical double reflector, $F_m/D_m = 0.6$ for main reflector, $f = 30$ GHz [11].](image)

Next, we investigate the aperture efficiency and field distribution cuts for different scan angles. Results are presented in Fig. 18. It is clear that, with increasing scan angle, the region of maximum power becomes larger, but it is less shifted from the center, as compared to a prime-focus reflector or double-parabolic reflector. We observe a more uniform distribution of power over the array elements. This is significantly improved compared to the investigated configurations in section II and III, where there are elements with zero aperture efficiency like in Fig. 6 and Fig. 11 for the $1.5^\circ$ and $3^\circ$ scan case. At the same time, the number of active elements is significantly increased. The required overall array dimensions are also much smaller as
compared to the double parabolic reflector from section III. A comparison of the investigated reflector configurations is given in Table I. The comparison criteria have been analyzed for field distributions at the FPA surface at 30 GHz and for a target aperture efficiency of 80%.

Figure 18. Aperture efficiency and electric field cuts for different angle of incidence of the incident field in the array plane of an optimised symmetrical double reflector, \( F_p/D_p = 0.6 \) for main reflector, \( f = 30 \) GHz.

<table>
<thead>
<tr>
<th>Comparison Criteria</th>
<th>Wave incid.</th>
<th>A classical prime-focus reflector</th>
<th>A double parabolic reflector</th>
<th>Optimized FPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of illuminated elements</td>
<td>0°</td>
<td>8</td>
<td>−1600</td>
<td>−550</td>
</tr>
<tr>
<td></td>
<td>1.5°</td>
<td>8</td>
<td>−1600</td>
<td>−610</td>
</tr>
<tr>
<td></td>
<td>3°</td>
<td>8</td>
<td>−1600</td>
<td>−670</td>
</tr>
<tr>
<td>Required array size</td>
<td>0°</td>
<td>0.6 cm</td>
<td>8.5 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td></td>
<td>1.5°</td>
<td>1.9 cm</td>
<td>17.7 cm</td>
<td>7.8 cm</td>
</tr>
<tr>
<td></td>
<td>3°</td>
<td>3.4 cm</td>
<td>28 cm</td>
<td>11.5 cm</td>
</tr>
<tr>
<td>Scan performance: percent of active elements from whole array</td>
<td>0°</td>
<td>−100 %</td>
<td>−100 %</td>
<td>−100 %</td>
</tr>
<tr>
<td></td>
<td>1.5°</td>
<td>−9.9 %</td>
<td>−22.8 %</td>
<td>−44.9 %</td>
</tr>
<tr>
<td></td>
<td>3°</td>
<td>−3.1 %</td>
<td>−9.1 %</td>
<td>−22.7 %</td>
</tr>
<tr>
<td>Phase linearity (see Fig. 17) and rms error</td>
<td>Completely nonlinear</td>
<td>Linear inverted V-kind of shape</td>
<td>Linear V-kind of shape</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.36°</td>
<td>3.06°</td>
<td>1.65°</td>
<td></td>
</tr>
</tbody>
</table>

V. CONCLUSION

We have presented a double reflector configuration which shows excellent performance of a wide frequency range in terms of maximizing the number of simultaneously active array elements. Up to 22.7% of elements are active simultaneously within a scan range of \( \pm 3\). It also overcomes the well-known FPA problem of a small illuminated region in the focal plane by increasing it by a factor of 60, as compared to traditional prime-focus configurations. The phase linearity between the array elements has been improved to an rms error of 1.65° at 30 GHz. In addition, the scanning capabilities have been significantly improved as compared to classical prime focus and double-parabolic reflectors. The beam deviation decreased by a factor of 2.5, as compared to a double-parabolic configuration, for a scan range between \( \pm 1.5\). Combined with wideband photonic beamforming, this antenna configuration can result in a wideband, compact, low-weight and energy efficient antenna system for Ka-band communications.

REFERENCES