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Effects of Bending a Planar Antenna Array on Its Scan Performance

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Abstract—The effects of cylindrically bending of a linear planar antenna array is investigated in order to improve the scan range for 60 GHz indoor applications. The scan range of the bent antenna array can be significantly increased by a proper choice of the array bending angle, antenna element number, and element beamwidth. A bent array based on the BFACP antenna is presented as an example. With the use of an appropriate rectangular array configuration instead of a linear array, the array form factor can be reduced and the array beamwidth can be controlled according to the design requirements while keeping the scan range enhancement provided by bending the array.

I. INTRODUCTION

The 60-GHz frequency band is getting increasing attention in order to design short range, multi-gigabit-per-second wireless communication systems [1]. One of the major reasons is the availability of large amount of license-free spectrum at 60 GHz worldwide. Moreover, low-cost high-frequency circuits have been developed with the use of SiGe and CMOS technologies. In addition, the wavelength is about the chip dimension at 60 GHz, which allows antenna arrays to be integrated into the system package or even on the chip. Due to the oxygen absorption at 60 GHz, extra spatial isolation is naturally provided for short range communications.

Therefore, 60-GHz millimeter wave communication systems can be employed by many consumer electronics applications, for instance, wireless uncompressed high definition video streaming for 1080p HDTV, which requires a 3–4.5 Gbps data rate. As a result, to obtain sufficient link budget required for 60 GHz, high gain antenna arrays with high radiation efficiency are needed. In addition, such kind of applications suffer from human body blockage due to people’s movement, which is generally more than 20 dB at 60 GHz in a typical indoor environment [2]. This requires antenna arrays to support beamforming. Based on these requirements, a planar antenna array consisting of a balanced-fed aperture-coupled patch (BFACP) antenna has been investigated [3], [4], which can provide a ±30◦ scan range.

In order to achieve better coverage for indoor environment, the scan range of the antenna array needs to be further increased. However, a typical planar antenna array has limited beam steering capability due to the non-uniform element pattern which leads to low directivity at scan angles far from broadside. Conformal antenna arrays on the surface of a cylinder or sphere have the potential of 360◦ azimuth coverage or even full space coverage [5]. Because in this way, every direction of interest is covered by a certain group of source elements. Therefore, it is possible to enhance the scan range by cylindrically bending an antenna array. In practice this means the use of flexible PCB. In this work, the effects of the bending angle of the cylindrical array, the beamwidth of the antenna element, and the number of antenna elements on the scan range are investigated in order to improve the array coverage and to provide guidelines for conformal antenna array design. As an example, a bent array based on the BFACP antenna will be analyzed. It is shown that with the correct choice of array bending angle, element number, and beamwidth, the scan range of the bent antenna array becomes significantly larger compared to the linear array configuration, e.g. more than ±90◦ instead of ±50◦. The bending effects of rectangular array configuration are also examined, which can provide extra parameters to control the array form factor and array beamwidth.

II. FORMULATION OF BENT ANTENNA ARRAY

The geometry of the problem studied in this paper is shown in Fig 1. The linear planar antenna array has N identical radiating elements with equal element spacing d = 0.5λ. It is bent cylindrically to an arc, where O is the center of the arc, θb is the subtended angle of the arc, and R is the radius of the arc. When the bending angle θb → 0° the antenna array can be considered as a linear planar array, and when the bending angle θb = 360° the antenna array becomes a cylindrical array.

![Fig. 1. Cylindrically bent antenna array.](image-url)

Each antenna element \( n \) points in the radial direction with
the local angular coordinates \((\theta'_n, \phi'_n)\). The directivity pattern of the antenna element \(D(\theta'_n, \phi'_n)\) is modelled as

\[
D(\theta'_n, \phi'_n) = \left\{ \begin{array}{ll} 
2(m + 1) \cos^n(\theta'_n), & 0^\circ \leq \theta'_n \leq 90^\circ, 0^\circ \leq \phi'_n \leq 360^\circ \\
0 & \text{elsewhere}
\end{array} \right.
\]

where \(m \geq 0\). Therefore, the half-power beamwidth (HPBW) of the antenna element is controlled by \(m\). As shown in Table I, when \(m\) becomes larger, the beamwidth becomes narrower and the maximum directivity becomes larger.

**TABLE I**

<table>
<thead>
<tr>
<th>(m)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPBW ((^\circ))</td>
<td>151.0</td>
<td>120</td>
<td>90</td>
<td>74.9</td>
<td>65.5</td>
</tr>
<tr>
<td>(D_{\text{max}}) (dBi)</td>
<td>4.8</td>
<td>6.0</td>
<td>7.8</td>
<td>9.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

The power or radiation intensity pattern of the antenna element can be calculated by

\[
P_n(\theta'_n, \phi'_n) = \frac{P_{\text{rad,n}}}{4\pi} D(\theta'_n, \phi'_n)
\]

where \(P_{\text{rad,n}}\) is the radiated power by element \(n\). Thus the amplitude of the electric-field intensity in the far-field zone is obtained

\[
|E_n(r, \theta'_n, \phi'_n)| = \sqrt{\frac{2\eta P_{\text{rad,n}} D(\theta'_n, \phi'_n)}{4\pi r^2}}
\]

where \(r\) is the distance from the reference point \(O\) to the far-field observation point and \(\eta\) is the intrinsic impedance of the medium.

The bending array can focus the beam in the direction \(\theta_b\) when cophasal excitations are applied to each element. Neglecting the mutual coupling effects, the electric-field intensity in the far-field zone of the bent array in the bending plane can be expressed as

\[
E(\theta) = \sqrt{\sum_{n=1}^{N} \frac{2\eta P_{\text{rad,n}} D(\theta-\theta_n)}{4\pi r^2}} e^{jkr[\cos(\theta-\theta_n)-\cos(\theta_b-\theta_n)]}
\]

in which

\[
\theta_n = (n - \frac{N + 1}{2}) \frac{\theta_b}{N}, \quad n = 1, 2, ..., N
\]

and \(k\) is the wavenumber, \(k = 2\pi/\lambda\). Therefore, the directivity of the antenna array at scan angle \(\theta_0\) is given by

\[
D(\theta_0) = \frac{n^2|E(\theta_0)|^2}{2\pi} \frac{P_{\text{rad,n}}}{4\pi}
\]

\[
= \left[ \sum_{n=1}^{N} \sqrt{P_{\text{rad,n}} D(\theta_0 - \theta_n)} \right]^2
\]

\[
= \sum_{n=1}^{N} P_{\text{rad,n}}
\]

If the radiated power of each element is assumed to be identical, (6) becomes,

\[
D(\theta_0) = \frac{\left[ \sum_{n=1}^{N} \sqrt{D(\theta_0 - \theta_n)} \right]^2}{N}
\]

The gain of the antenna array at scan angle \(\theta_0\) in dBi is given by

\[
G(\theta_0) = 10 \log_{10} v_{cd} D(\theta_0)
\]

where \(v_{cd}\) is the radiation efficiency of antenna element.

**III. RESULTS AND DISCUSSION**

Using (7), the directivity at different scan angles \(\theta_0\) of an 8 elements antenna array \(N = 8\) with bending angle \(\theta_b = 1^\circ, 90^\circ, 120^\circ, 180^\circ, \) and \(360^\circ\) is shown in Fig. 2 for \(m = 1\). It is seen that the directivity of the approximate linear array is always larger than that of the bent arrays when the scan angle \(\theta_0\) is smaller than around 80°.

Fig. 3 shows how the directivity of the antenna array varies with scan angle for different element power patterns. It is seen that when the beamwidth of element pattern becomes narrower \((m = 2\) and \(m = 3\)), the directivity of the bent array becomes larger than that of linear array starting from around \(\theta_0 = 65^\circ\) for the case of \(m = 2\) and \(\theta_0 = 55^\circ\) for the case of \(m = 3\). This is because the antenna element power pattern becomes more concentrated on the radial direction when \(m\) becomes larger. When the antenna array is bent, the radiation power of the array is spread out to achieve a larger scan range, which can compensate the effect of the narrower beamwidth. Therefore, the beamwidth is an important factor for the bent antenna array design.

Fig. 4 shows the 3 dB scan range of the maximum directivity as a function of the bending angle. This scan range is defined as the range from the broadside direction of the array to the scan angle at which the directivity of the antenna array becomes 3 dB lower than the maximum directivity. The maximum scan angle studied in this paper is limited to 90°. It is shown that when the element pattern beamwidth is narrow, e.g., \(m \geq 2\), the scan range can always be increased by bending the antenna array. When the bending angle is large enough, e.g., \(\theta_b > 250^\circ\), the scan range can always be larger than 90° for all the element patterns presented in this figure. This is because the bending antenna array behaves more and more like a cylindrical array.
However, in practical antenna design, there is always a specific requirement on antenna gain or directivity. In this paper, a 15 dBi required directivity is assumed. Fig. 5 shows the 3 dB scan range, i.e. a directivity within that range, above 12 dBi. It is seen that the directivity of the antenna array cannot achieve the requirement when the bending angle is large, e.g., $\theta_b > 200^\circ$. It is also shown that when the beamwidth is narrow, e.g., $m \geq 3$, the scan range can be increased within an appropriate range of bending angles.

For 60-GHz applications, it is also desired to use the maximum EIRP within the whole scan range [6]. It means that the directivity of the antenna array at different scan angles should be as constant as possible. As a result, the scan range should be defined to fulfil both requirements presented in Fig. 4 and Fig. 5. Fig. 6 shows the combination of the results of Fig. 4 and Fig. 5. For a fixed bending angle, the directivity of antenna array is always higher than the required 12 dBi and the directivity difference within the corresponding maximum scan angle is always lower than 3 dB. It is seen that when the beamwidth becomes narrow, e.g., $m = 3$, the scan range is increased from about 37° to about 50° by bending the linear array with $\theta_b = 140^\circ$.

In order to further enhance the scan range, more antenna elements are needed. Fig. 7 shows the case of $N = 16$. 

Fig. 3. The directivity versus scan angles with different element power pattern.

Fig. 4. The 3 dB scan range of the maximum directivity.

Fig. 5. The 3 dB scan range of the required directivity.

Fig. 6. The combined 3 dB scan range with $N = 8$. 
Compared to the case of $N = 8$, the scan range is significantly increased for larger bending angle. This is because when the number of antenna elements is increased, the directivity requirements can be achieved for larger bending angle. For instance when $m = 3$, the scan range is increased from about $37^\circ$ to larger than $80^\circ$ if the bending angle $\theta_b$ is within the range between $200^\circ$ and $260^\circ$.

Instead of placing elements along a line, the configuration of a rectangular planar antenna array can be used to increase the number of antenna elements. This configuration can provide smaller form factor than the linear antenna array with the same bending angle. Furthermore, the array pattern will become more symmetrical with lower side lobes [7]. Fig. 8 shows the case of bending a rectangular array with a $2 \times 8$ configuration. It is observed that the variation of maximum scan angle with the bending angle is similar to that in the $1 \times 16$ configuration shown in Fig. 7. Therefore, the maximum scan angle more relies on the number of antenna elements than the configuration. As a result, with the same number of antenna elements, the radius of the bent array can be reduced by bending a rectangular array instead of bending a linear antenna array with a fixed bending angle.

Using the rectangular array configuration also introduces extra parameters to control the pattern of the array, such as the beamwidth. Fig. 9 shows the HPBW in the scan plane and in the array broadside direction of different array configurations when $m = 3$. It is seen that for a fixed bending angle, the HPBW becomes larger when the number of antenna elements in the scan plane becomes smaller. Typically a $30^\circ$ array beamwidth is desired for WPAN applications in order to reduce the requirement of the alignment accuracy [8]. It is found that the $2 \times 8$ array configuration can provide around $30^\circ$ HPBW when the bending angle $\theta_b$ is about $250^\circ$, which is larger than $80^\circ$ as well.

### IV. AN EXAMPLE WITH BFACP ANTENNA

In the following, the BFACP antenna [3] is employed as array element as a practical study case. Fig. 10a shows the geometry of the BFACP antenna, and Fig. 10b shows the antenna element pattern which is extracted from the simulation results of CST Microwave Studio at $60$ GHz. The HPBW of the radiation pattern is $102^\circ$ in E-plane and $69^\circ$ in H-plane. Compared with Table I, the HPBW of E-plane is between $m = 1$ and $2$, and the HPBW of H-plane is between $m = 3$ and $4$. This also implies that the values of $m$ studied in this paper are within practical range.

Fig. 11 shows the combined $3$ dB scan range of the BFACP antenna array for E-plane and H-plane alignment with the cylinder axis. It is seen that the scan range cannot benefit from bending the array for both cases when $N = 8$. This is because
Fig. 11. The combined 3 dB scan range of the BFACP antenna array.

The maximum directivity of the BFACP antenna is lower than the directivity of cosine-like pattern assumed in (1) with the same HPBW. Therefore, with 8 antenna elements, it is not possible to compensate the directivity loss due to the bending effect. But with increasing the number of array elements $N$, the scan range can be significantly increased by bending the array. For instance, in the case of H-plane alignment, the maximum scan angle of the linear array is about $51^\circ$. When an array with 16 elements is bent between $210^\circ$ and $330^\circ$, the maximum scan angle can be increased to more than $90^\circ$.

V. CONCLUSIONS

In this paper, the effects of cylindrically bending of a linear planar antenna array is analyzed in order to improve the scan range which is crucial for 60 GHz indoor applications. The bending angle of the antenna array, the beamwidth of the antenna element, and the number of array elements are examined using a cosine-like element pattern and the BFACP antenna pattern. It is found that the scan range of the bent antenna array can be significantly increased, e.g. from about $50^\circ$ to more than $90^\circ$, by an appropriate setting of these parameters. The bending effects of rectangular array configurations are also examined. It is observed that with a proper choice of the array configuration, the array form factor can be reduced and

the array beamwidth can be controlled according to the design requirements without losing the scan range. This information can also provide guidelines for our further conformal antenna array design using flexible PCB. The effect of mutual coupling on the scan range will be considered in the future work.

REFERENCES