An Array of Coupled Nonradiative Dielectric Waveguide Radiators

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***Abstract*—A novel antenna array that radiates a single mode of multiple coupled nonradiative dielectric (NRD) waveguides, is described. The array is fed by a single NRD waveguide, which is designed to propagate a wave with the same wave number as that of free-space. The individual radiators of the array are spaced at one free-space wavelength, but due to the narrow beamwidth of the individual radiators, grating lobes are effectively suppressed. An eight-element array is described and measurements presented, but the design method can be extended to any number of elements.**

***Index Terms*—Antenna arrays.**

I. Introduction

A number of authors have recently described new antenna configurations in nonradiative dielectric (NRD) waveguide [1]–[5]. These antennas all fall into the broad category of antennas that radiate either as open-ended single or coupled NRD waveguides or as the unidirectional radiator (UDR). The antenna described in [5] radiates as four elements of an infinite array of coupled NRD waveguides, driven by a corporate feed network [6].

Other antennas in NRD waveguide make use of a variety of radiating mechanisms, such as radiation through slots in the conducting plane [7]–[10], leaky-wave structures using various mechanisms [11]–[15], and radiation from variously terminated guides [16]. All these antennas have the same advantage in common, namely that they can be integrated directly into an NRD waveguide circuit. The latter has been proven to be a cost-effective low-loss guiding medium at microwave and millimeterwave frequencies.

The radiation properties of an open-ended section of NRD waveguide were described in [4], and it was shown that the aperture field can be adequately approximated by the fundamental LSM waveguide mode. In [5], the same principle was applied to radiation from an array of elements that have the properties of elements in an infinite array, and it was once again shown that the fundamental LSM-mode approximation is acceptable. In the latter work, the properties of the infinite array were achieved by introducing two conducting planes, on either side of the coupled NRD guides. The array was fed by a corporate feed network.

The construction of the array described in [5] is well suited to small arrays, but for large arrays the corporate feed network would become very large. In this paper, an antenna array is described that makes use of a series feed for the radiating elements, by coupling into a single run of NRD waveguide, as shown in Fig. 1. A variety of other antennas that are also fed from one end by a single run of waveguide have been described, such as [17] where a series of dielectric image guides with metal disk perturbations are fed from a metal waveguide, and in [18] where a leaky NRD waveguide is used to feed a planar antenna array of slots in a metal plane. In this construction, however, the NRD waveguide is used in integrated fashion.

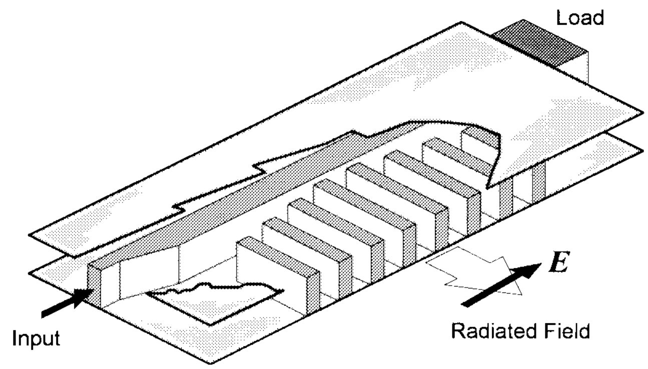

Fig. 1. Physical construction of antenna array.

The construction of the array further makes it impossible to introduce reflecting planes beyond the end elements. The propagation velocity on the NRD feed guide is a function of its width, and it is designed to have a propagation velocity approximately equal to that of free space. This dictates a wide guide, with the fields strongly concentrated in the dielectric, and consequently very light coupling to the coupled NRD guide elements, making the method of construction ideally suited to large arrays. In order to prove the principle, however, it was decided to employ only eight elements, and dissipate the unradiated energy in a matched load. In a large practical array, the excitation could be by either traveling or standing wave.

A multitude of modes can exist on the eight coupled NRD waveguides, depending on how they are excited. In general, an arbitrary excitation would stimulate a combination of modes that travel at different velocities, so that a given excitation of the radiating rods will not lead to the same distribution of amplitudes in the aperture. In what follows, the basic mode that exists for eight coupled NRD waveguides excited in phase is determined, and the corresponding amplitudes on the eight guides obtained. The guides are then excited using these amplitudes; the amplitudes in the radiating aperture correspond to the exciting amplitudes. This procedure implies a

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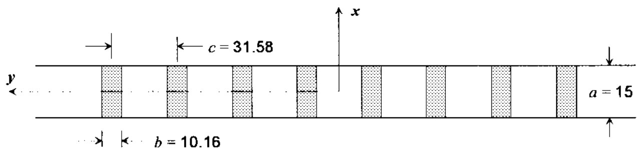
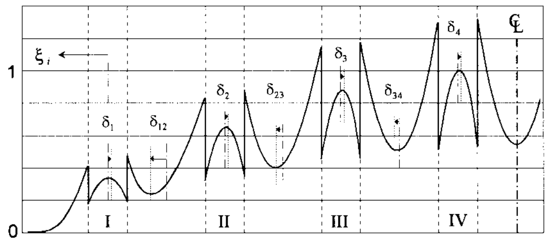


(a)



(b)

Fig. 2. (a) Array of eight coupled NRD guides. (b) The electric field strength.

single, unique solution. However, it is possible to obtain other aperture distributions by choosing an appropriate combination of modes.

II. Coupled NRD Waveguides: Fundamental Mode

Fig. 2 shows the geometry of eight coupled NRD waveguides (guides), spaced at a distance of c between the center lines. The dielectric width is b, and the distance between the plates is a, a being less that one half free-space wavelength. The behavior of the fields in this type of configuration has been widely described, and is not repeated here in any detail. In the region away from the coupled lines, the field falls away exponentially as

$$e^{-\alpha_y(b/2-\xi)}$$

where ξ is the variable in the direction y, centered on the center line of the end guide. The fields in the direction y are not symmetrical about the center lines of the individual radiators, due to the fact that the structure is not symmetrical about the individual radiators. In the areas between the coupled dielectric regions, there exist fields that are distributed as functions of the type

$$\cosh[\alpha_y(c/2-b/2-\xi+\delta_{ij})]$$

where ξ is measured from a specific center line, and δ_{ij} is the distance by which the field minimum is offset from the center line; it depends on which area between two guides is being considered. The fields in the dielectric regions will vary as

$$\cos[\beta_y(\xi+\delta_i)]$$

and where δ_i is the amount by which the field maximum in a specific guide is offset from its center line, as shown in Fig. 2(b).

The wave numbers α_y for the various air-filled regions, and β_y for the various dielectric-filled regions, must all be the same to ensure the existence of a single mode in the array of coupled NRD guides. By applying transverse resonance, the following transcendental equations are obtained at the interfaces between

TABLE I
Propagation Constants

α_y	β_y	β_z
143.16	202.16	127.35

the various regions, where [R] refers to the right-hand side of the dielectric, as shown in Fig. 2, and [L] to the left

Dielectric I [L]:

$$\frac{\alpha_y}{j\omega\mu_0\epsilon_0}=\frac{\beta_y}{j\omega\mu_0\epsilon_0\epsilon_r}\tan[\beta_y(b/2+\delta_1)]$$

or

$$\alpha_y\epsilon_r=\beta_y\tan[\beta_y(b/2+\delta_1)] \tag{1}$$

Dielectric I [R]:

$$\beta_y\tan[\beta_y(b/2-\delta_1)] = \alpha_y\epsilon_r\tanh[\alpha_y(c/2-b/2-\delta_{12})] \tag{2}$$

Dielectric II [L]:

$$\alpha_y\epsilon_r\tanh[\alpha_y(c/2-b/2+\delta_{12})] = \beta_y\tan[\beta_y(b/2+\delta_2)] \tag{3}$$

Dielectric II [R]:

$$\beta_y\tan[\beta_y(b/2-\delta_2)] = \alpha_y\epsilon_r\tanh[\alpha_y(c/2-b/2-\delta_{23})] \tag{4}$$

Dielectric III [L]:

$$\alpha_y\epsilon_r\tanh[\alpha_y(c/2-b/2+\delta_{23})] = \beta_y\tan[\beta_y(b/2+\delta_3)] \tag{5}$$

Dielectric III [R]:

$$\beta_y\tan[\beta_y(b/2-\delta_3)] = \alpha_y\epsilon_r\tanh[\alpha_y(c/2-b/2-\delta_{34})] \tag{6}$$

Dielectric IV [L]:

$$\alpha_y\epsilon_r\tanh[\alpha_y(c/2-b/2+\delta_{34})] = \beta_y\tan[\beta_y(b/2+\delta_4)] \tag{7}$$

Dielectric IV [R]:

$$\beta_y\tan[\beta_y(b/2-\delta_4)]=\alpha_y\epsilon_r\tanh[\alpha_y(c/2-b/2)]. \tag{8}$$

The propagation constants in the various regions are connected through

$$\beta_z^2=k^2+\alpha_y^2-(\pi/a)^2=k^2\epsilon_r-\beta_y^2-(\pi/a)^2. \tag{9}$$

By solving these equations for the dimensions $a=15$ mm, $b=10.16$ mm, $c=31.58$ mm, and $\epsilon_r=2.55$, the propagation constants and offsets from the center lines shown in Tables I and II are obtained.

The electric field strengths in the air- and dielectric-filled regions are shown in Table III. The values on the left (E_L) and on the right (E_R) as well as the maxima (in the dielectric) and

TABLE II
OFFSETS (mm)

δ_1	δ_{12}	δ_2	δ_{23}	δ_3	δ_{34}	δ_4
0.188	2.136	0.081	1.006	0.039	0.434	0.012

TABLE III
ELECTRIC FIELD STRENGTH

	E_L	Max/Min	E_R
Air 0 - I	-	-	0.4221
Dielectric Region I	0.1655	0.3417	0.1878
Air I - II	0.4788	0.2584	0.8333
Dielectric Region II	0.3268	0.6492	0.3450
Air II - III	0.8797	0.4129	1.1433
Dielectric Region III	0.4483	0.8780	0.4602
Air III - IV	1.1735	0.5120	1.3141
Dielectric Region IV	0.5153	1.0000	0.5195
Air IV - Centre	1.3247	0.5464	-

minima (in the air) are shown for each region. The calculations were based on a normalized maximum field strength of one in region IV. Note that only one half of the values are shown in both the table and in Fig. 2.

III. ANTENNA CONSTRUCTION

The field distribution around each of the guides in the array nominally resembles that of the distribution around the guides in the even-sum-mode of [5], where it was found that the individual guide radiation pattern was sharp enough to suppress grating lobes at radiating element spacings of up to one free space wavelength, and it was assumed that this property would also hold for the case under consideration. The array was designed with an interelement spacing of nominally one free space wavelength. To achieve an in-phase excitation, the propagation velocity on the feeding guide had to be approximately equal to that of free space. With a width of 20 mm, and a plate separation of 15 mm, the propagation constants for the feeding line are found to be as shown in Table IV. This gives a guide wavelength of 31.62 mm, or 1.001 times the free space wavelength at the design frequency of 9.5 GHz (note that as there are no resonant elements in the array, this frequency is not critical). The dielectric used was irradiated polystyrene with $\epsilon_r = 2.55$. The eight coupled sections of NRD guide are fed by end coupling at right angles to the feed section of NRD guide, as shown in Fig. 3.

The slight variation from free space velocity in the feed line will cause the main beam to squint slightly, and will prevent summation of the reactances caused by the coupling of the radiating elements to the feed line.

In order to calculate coupling of the radiating guides to the feed guide, measurements of coupling between the feeding NRD line and individual radiators were performed, and Fig. 4 shows the relationship between coupling and gap between the

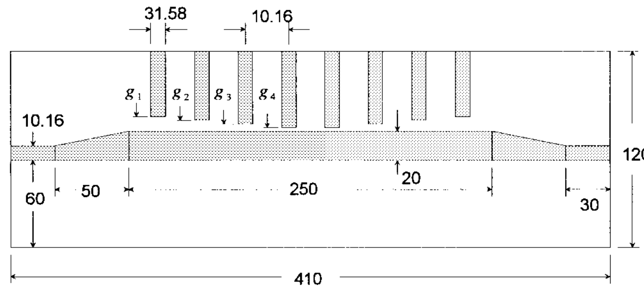


Fig. 3. Physical dimensions of antenna array (mm).

TABLE IV
PROPAGATION CONSTANTS

α_y	β_y	β_z
209.18	132.70	198.69

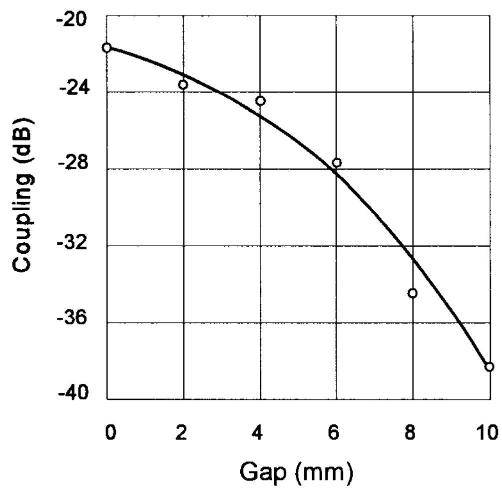


Fig. 4. Coupling between radiator and feed line.

TABLE V
COUPLING GAPS (mm)

g_1, g_8	g_2, g_7	g_3, g_6	g_4, g_5
7.3	5.2	1.5	0

feeding line and a single radiating line. Note that this is only an approximation of the situation that would exist when all eight guides are coupled to the feeding guide. The reason for that is that the field distribution in the vicinity of each of the individual guides differs from that of the case where only a single guide is coupled. This is appreciated when noting the field distributions depicted in Fig. 2(b), and comparing it to the case of a single line, which decays away symmetrically to zero either side of the dielectric region [much as on the left-hand side of line I in Fig. 2(b)].

From this information, the coupling gaps g_1 to g_4 are obtained; the coupling gaps are shown in Table V.

IV. ANTENNA MEASUREMENTS

Fig. 5 shows the E-plane radiation pattern for the array. The main beam is well formed, with a slight squint, and the

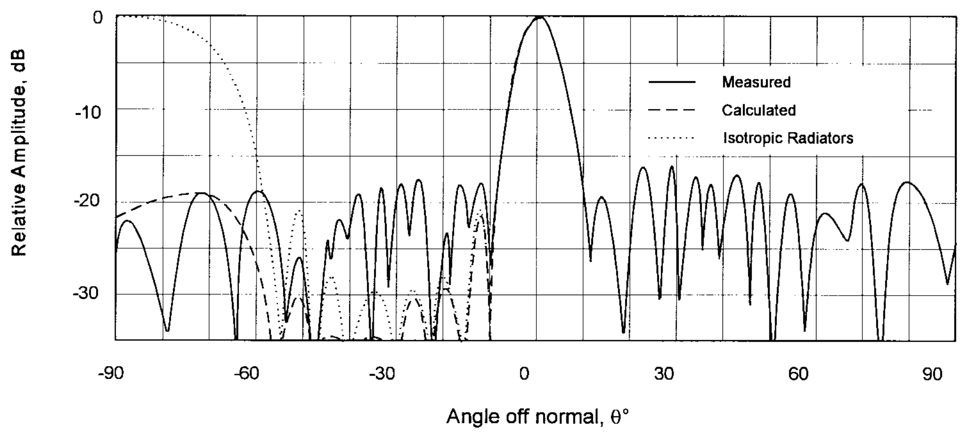


Fig. 5. Measured and calculated radiation pattern for eight-element array, E-plane. The pattern for an array with isotropic radiators is also shown.

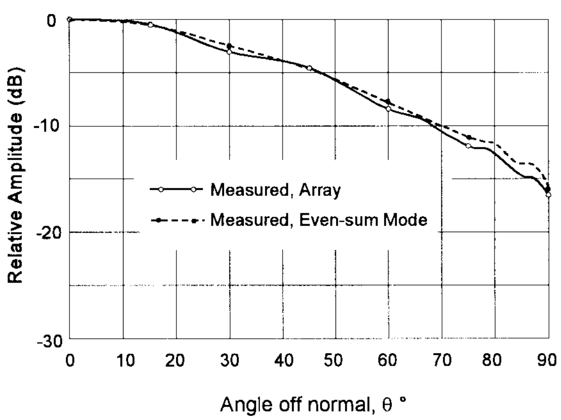


Fig. 6. Measured radiation pattern for eight-element array, and pattern for even-sum mode, H-plane.

worst sidelobes are 17 dB below the main beam peak. Also shown in Fig. 5 are the predicted radiation patterns for the NRD array, and an array of isotropic radiators. The sidelobes between 20 and 50° exceed the predicted levels. This is due to the uncertainty in determining the coupling, and calculating the corresponding gaps, both because of the inaccuracy of the measurements, and the approximation discussed above. The suppression of the large grating lobe beyond 60° is very close to the prediction. Fig. 6 shows the H-plane radiation pattern of the array. This corresponds to the H-plane performance previously measured for radiation from the even-sum mode [5].

The main beam has half-power beamwidths of $8.3° \times 64.0°$. Using the approximate relationship of $G = 26\,000/(\Theta_1\Theta_2)$ the gain is calculated as 16.9 dB, *excluding* the power dissipated in the load. This compares to the gain for a uniformly illuminated aperture of the same size of 16.8 dB.

V. Conclusion

The design and performance of an eight-element coupled NRD-guide antenna array has been described. The correspondence between measured and predicted radiation properties is good, except for a deterioration of sidelobe performance due to inaccurate characterization of the coupling properties between radiating guides and the feed guide. Even at spacings as large as one free space wavelength, grating lobes are effectively suppressed due to the sharp radiating pattern of the elements.

If the value of the end offset δ_1 is calculated for an increasing number of coupled radiating guides, it is found that it tends to a limit for more than eight elements. This indicates that if the number of coupled guides were increased substantially, the last four elements on either end of the array would have couplings very similar to those treated here, while the center elements tend to be similarly coupled, and again nominally similar to the inside guides of this example. In such cases there will be a taper on the edges of the aperture, but the excitation will be fairly flat across the center of the (large) array.

The properties discussed here would be most suitable for application to the construction of large linear arrays, where the natural end taper, combined with the ease of obtaining variable coupling, would contribute to the design of arrays with low sidelobe levels. The fact that the array can be constructed integrally with the rest of an NRD waveguide circuit is particularly attractive where planar construction is indicated. As with all antennas that are serially fed from a single guide, the bandwidth is intrinsically limited.

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