Multi-layer spatial angular filter with air gap tuner to suppress the grating lobes of microstrip patch arrays

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Abstract — **In this paper, we propose a multi-layer spatial angular filter containing periodically high and low permittivity dielectric layers and air gap tuners to suppress the grating lobes of microstrip patch antennas. When the filter is applied to a 16x16 phased array with many grating lobes due to the 2.8λ spacing between adjacent phase shifters, we show that the grating lobes, which induce interference among satellites, are completely eliminated outside the ±30° range.**

I. Introduction

The transmitting and receiving antenna on a satellite is usually steered mechanically when the scanning angle is large. However, for fine adjustment of the scanning angle, it is steered electronically by phase shifters attached to the antenna. Since the range and resolution of a phase shifter are limited, the separation between adjacent radiators in the array should usually be more than one wavelength. As a consequence, many grating lobes from the array appear. In this case, a spatial angular filter with characteristics of both good transmission near the main beam region and reflection at the other regions, is required to reduce the grating lobe and side-lobe level [1]. Such angular filters for horn antennas are designed by using multi-layer dielectric structures [2][3] or a metallic screen [4].

Research on the design of the cover built with a two-dimensional PBG structures for improving the directivity of patch antennas is ongoing [5][6]. However, a 2-D PBG structure has characteristics that make it impractical. These include sensitivity of the frequency bandwidth because of the narrow bandwidth of the defect mode, and the difficulty of fabrication for 2-D PBG periodic structures, such as periodic dielectric rods or stacked wood files, above the substrate.

In order to enhance the directivity of printed circuit antennas, such as microstrip antennas consisting of substrate and ground plane, Jackson [7] et al. presented the superstrate–substrate resonance method, that is, dielectric layers stacked in a high–low dielectric sequence to receive fields with angular sensitivity in a prescribed direction. Yang [8] developed Jackson's method to multi-layer dielectric structures for more directive angular filters. However, the thickness of Yang's and of Jackson's substrates and superstrates are too thick ($\lambda_g/4$ or $\lambda_g/2$) to match because of their high inductance. In addition, problems of high loss and the requirement that a substrate be built to order are introduced.

In this paper, the thickness of the substrate and the superstrate for the antenna and angular filter are selected to be commercial standard thickness substrates, such as RT duroid 6008. An adjustable air gap tuner is placed between periodic dielectric layers, instead of quarter wave thickness substrates. The resulting angular filter has characteristics of easy matching, sharpness of angular filter pattern, and low loss.

In the final section we show the suggested angular filter applied to a 16x16 limited scan array antenna to reduce grating lobes and side-lobes in the interference region.

II. The Multi-layer Angular Filter

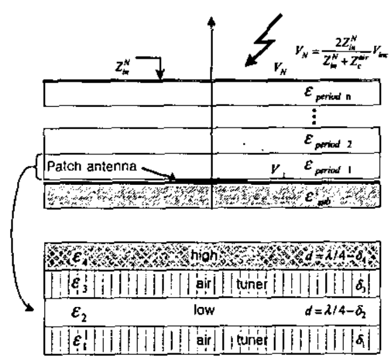

Fig. 1. Structure of the multi-layer dielectric angular filter.

Figure 1 represents the multi-layer dielectric angular filter structure. As shown in Figure 1, the periodic layers contain the high permittivity layer, the low permittivity layer, and air gaps. The layers are stacked in the dielectric sequence high-air-low-air. The air gaps δ_1 and δ_3 have

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been used to compensate for reducing the thickness of the high–low dielectric layer and the dielectric loss. By tuning the thickness of the air gaps, the characteristics of the angular filter have been conserved, although the thickness of the high–low dielectric layer is reduced. When the number of periodic layers is increased, the sharpness of the angular filter is improved. However, this improvement in the characteristics of the angular filter is accompanied by degradation of the frequency characteristics. In this paper, period n is limited to two layers, which is a trade-off between the filter's angular and frequency characteristics.

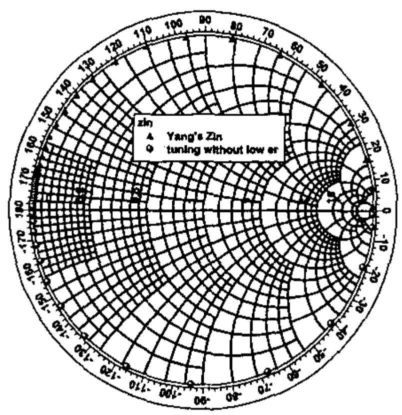

Fig. 2 Yang's input impedance vs. input impedance for using the tuning technique without a low ε_r layer.

By using transmission line analysis and reciprocity [7], the input impedance at the layer interface and the antenna pattern are obtained, as shown in Figures 2 and 3. Figure 2 represents the input impedance as a function of the incidence angle at the interface of the angular filter. As show in Figure 2, the broadside direction incident angle is located at the open circuit point ($Z_{in}=\infty$) on the Smith chart, and most of the other incident angles are located at the short circuit point ($Z_{in}=0$). Because V_n is maximized when Z_{in} is infinite, from the equation given in Figure 1, the result from the Smith chart shows that the maximum voltage is transmitted to the layer interface when the input impedance at the interface is near infinity. In addition, the sharpness of the angular filter is estimated from the spacing of points near the open point in the Smith chart. The points from the upper part of the Smith chart show the input impedance for Yang's [8] layer, and the points from the lower part of the Smith chart show the conjugate input impedance for using the tuning technique with an air gap tuner instead of the low permittivity layer (Table I).

Jackson [7] and Yang [8] showed that the maximum voltage transfer occurs when the circuit system is in resonance. For the resonance condition, all the superstrates are a quarter wavelength and the substrate is a half wavelength. However, it is difficult to fabricate the printed circuit antenna above a thick substrate owing to the difficulty of matching a large inductance and an unwanted surface wave. As a result, printed circuit antennas require a thin substrate. Such a thin substrate cannot be applied for the superstrate–substrate resonance condition. For this reason, a tuning technique using an air gap is required for printed circuit antennas on a thin substrate.

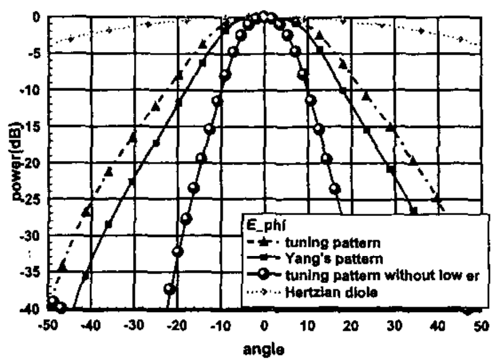

Fig. 3. Calculated Eϕ pattern tuning pattern vs. Yang's pattern.

Figure 2 is calculated from equations (1) and (2) by sequential substitution [7].

$$Z_{in}^{\ n+1} = Z_c^{\ n+1} \frac{Z_{in}^{\ n} + jZ_c^{\ n+1} \tan \beta^{n+1} d^{n+1}}{Z_c^{\ n+1} + jZ_{in}^{\ n} \tan \beta^{n+1} d^{n+1}} \qquad (1)$$

$$Z_{in}^{\ 1} = jZ_c^{\ 1} \tan \beta^1 d^1 \qquad (2)$$

Superscript n represents the number of the stacked layer, and Z_c [7] is the characteristic impedance of the dielectric layers for transmission line analysis. Z_{in1} is the input impedance for the interface at the substrate above the ground plane.

$$\begin{pmatrix} V_N \\ I_N \end{pmatrix} = \begin{pmatrix} A_{period} & B_{period} \\ C_{period} & D_{period} \end{pmatrix}^N \begin{pmatrix} A_{sub} & B_{sub} \\ C_{sub} & D_{sub} \end{pmatrix} \begin{pmatrix} 0 \\ I_x \end{pmatrix} \qquad (3)$$

$$\begin{pmatrix} A_{period} & B_{period} \\ C_{period} & D_{period} \end{pmatrix} = \begin{pmatrix} A_{high} & B_{high} \\ C_{high} & D_{high} \end{pmatrix} \begin{pmatrix} A_{low} & B_{low} \\ C_{low} & D_{low} \end{pmatrix} \begin{pmatrix} A_{air} & B_{air} \\ C_{air} & D_{air} \end{pmatrix}^2$$

$$Z_c^n = \eta_0 n_n(\theta) / \varepsilon_n ,\ n_n(\theta) = \sqrt{n_n^2 - \sin^2(\theta)},\ n_n = \sqrt{\varepsilon_n \mu_n}$$

$$\beta^n(\theta) = k_0 \sqrt{n_n^2 - \sin^2(\theta)}$$

TABLE I

PARAMETERS OF SIMULATION

	ε_{sub}	ε_{r1}	ε_{r2}	ε_{r3}	ε_{r4}	dsub	d1	d2	d3	d4	Total d(mil)
Yang's layer	2.2	1.0	2.2	1.0	10.2	$0.25\lambda_g$ (156)	$0\lambda_g$ (0)	$0.25\lambda_g$ (156)	$0\lambda_g$ (0)	$0.25\lambda_g$ (75)	$1.25\lambda_g$ (618)
Tuning layer with air gap	3.38	1.0	2.2	1.0	10.2	$0.038\lambda_g$ (20)	$0.102\lambda_g$ (97)	$0.202\lambda_g$ (125)	$0.102\lambda_g$ (97)	$0.166\lambda_g$ (50)	$1.14\lambda_g$ (758)
Tuning without low ε_r dielectric layer	3.38	1.0	1.0	1.0	10.2	$0.038\lambda_g$ (20)	$0.106\lambda_g$ (101)	$0.25\lambda_g$ (236)	$0.106\lambda_g$ (101)	$0.166\lambda_g$ (50)	$1.29\lambda_g$ (996)

Figure 3 is obtained from the ABCD parameters and manipulation from Z_{in}. As shown in equation 3, A, B, C, and D are calculated from the transmission line equation with Z_c^n, β^n, d^n, where Ix is the current in the ground plane. Figure 3 shows the V_1 level as a function of incident angle. V_1 represent the transmitted voltage at the substrate interface above the ground plane as shown in (4).

$$V_1 = \frac{V_N}{A_{period}^{total} - jB_{period}^{total}\frac{\cot(\beta_{sub}d_{sub})}{Z_c^{sub}}} \quad (4)$$

A_{period}^{total} and B_{period}^{total} represent the A and B of $(ABCD)^N_{period}$, V_N is obtained from Zin^N, and Zc^{air} as shown in the equation of Figure 1. In addition, polarization dependency has been considered by adding the cos(θ) term for parallel polarization. As shown in Figure 3, the tuning pattern with an air gap has a similar characteristic to Yang's layer pattern (shown in Table I). However, in the case of tuning by insertion of an air gap, instead of a low dielectric layer, the pattern is narrower than the pattern for the other layers.

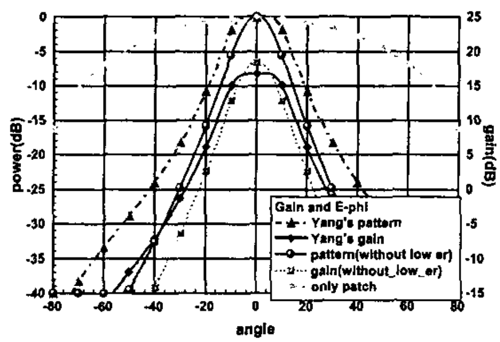

Fig. 4. Simulated gain and Eϕ pattern tuning vs. Yang's results.

Figure 4 shows the simulation result by using Ensemble 5.1. The width and length of the patch antenna is determined by the resonant frequency of TM_{01} and the other parameters are shown in Table I. This result has a similar trend to the calculated result (shown in Figure 3), but the differences between the two figures are the consideration of the surface wave and the difference of patterns for the patch antenna and a Hertzian electric dipole.

III. APPLICATION TO A 16X16 LIMITED SCAN ARRAY

The angular filter presented above was applied to a 16x16 phased array antenna design. It can reduce the cost because of the increased inter-element spacing without increased wide-angle side-lobe levels. Figure 5 represents a 16x16 limited scan array antenna which is composed of an angular filter, sixteen 4x4 sub arrays, sixteen phase shifters, and an RF feeder. That is, only sixteen phase shifters are required for maximum scanning from the broad side direction to ±10° when the inter-element phase, α, is 180°. The spacing between elements is $2.8\lambda_0$.

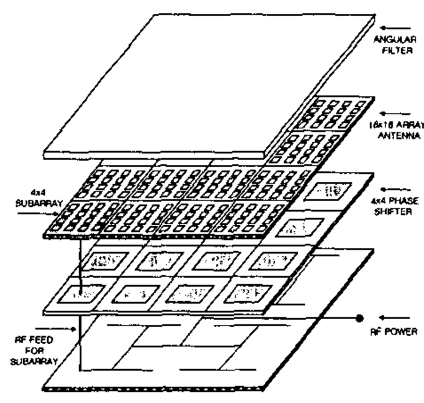

Fig. 5. 16x16 limited scan array antenna with phase shifter and RF feed.

In this case, for the planar array using an angular filter, the cost of the phased array antenna due to the many phase shifters and the complexity of the feed structure for reducing grating lobes and the side-lobe level has not been a concern of the phased array antenna designer.

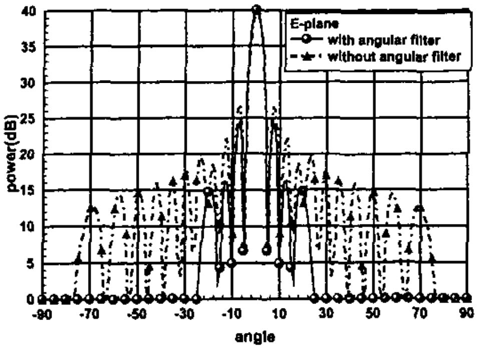

Fig. 6. Pattern of 16x16 array antenna for no phase shift (α=0°).

Figure 6 shows the E-plane simulation pattern for a 16x16 array antenna with inter-element phase, α, excited by a 0° phase shifter between elements. In addition, this pattern is obtained from the above single-element result. In this case, the E-plane pattern either with or without the angular filter has no grating lobes. The E-plane pattern using the angular filter shows that the side-lobe level is reduced from ±27°, and the first side-lobe level is reduced by approximately 4 dB.

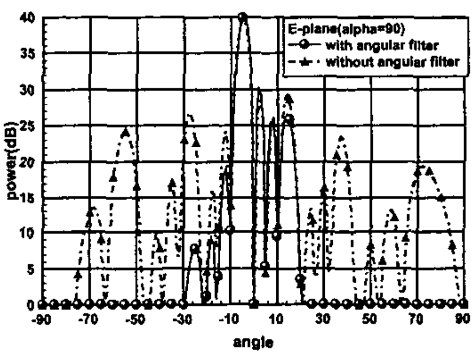

Fig. 7. Pattern of 16x16 array antenna for 90° phase shift (α=90°).

Figure 7 shows the simulated E-plane pattern when the inter-element phase, α, is 90° for a 5°-beam tilt angle. Because spacing between the phase shifters is $2.8\lambda_0$, grating lobes near 15°, 38°, 76°, -26°, -53° appeared for E-plane pattern without angular filter. However, in the case of the E-plane pattern using an angular filter, only the grating lobe near 15° is retained and the other grating lobes are eliminated. Because interference to other satellites is generally caused when the grating lobe is outside the ± 30° range, the array antenna using an angular filter is adopted for the limited scan array.

IV. Conclusion

We have used a multi-layer spatial angular filter for a 16x16 microstrip phased array to eliminate the grating lobes. The filter for a patch antenna with a thin substrate above the ground plane conserves the characteristic of sharpness of the angular filter by tuning the air gaps to compensate for the reduction in the thickness of the high–low dielectric layers. Simulation results of the pattern with the filter show that grating lobes and side lobes are eliminated outside the 30° range, and that the filter is suitable for a limited scan array.

Acknowledgment

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