Design and Analysis of Multisegment Dielectric Resonator Antennas

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***Abstract*—The multisegment dielectric resonator antenna (MSDRA) has recently been developed to significantly enhance the coupling to a microstrip line. The MSDRA greatly facilitates the integration with a printed feed distribution network for use in a large array environment. The thickness and permittivity of the dielectric insert of the MSDRA can be adjusted to match the element impedance to that of the feed line. A detailed study of the effects of varying the dielectric insert parameters was carried out and useful guidelines are presented for the design of MSDRA's.**

***Index Terms*—Dielectric resonator antennas.**

I. INTRODUCTION

DIELECTRIC resonator antennas (DRA's) offer versatility and design flexibility, making them attractive candidates for numerous applications. DRA's can be designed for narrow-band, multiband, or wide-band usage; can be made low profile or compact; can radiate linear or circular polarization; and can be used as an individual element or in a large planar array [1].

In an array environment, it is desirable to feed the DRA's with microstrip lines since this facilitates the integration of DRA's with printed feed distribution networks. Several linear arrays of DRA's fed by microstrip lines have been reported [2]–[6]. These arrays have all operated on the principle of the loaded transmission line. Each DRA in the array is positioned in close proximity to the transmission line and couples only a small amount of power from the transmission line. Thus, many DRA's are required in order for the array to radiate efficiently and to prevent a significant amount of power from reaching the end of the transmission line. The high number of DRA's required may not be practical, especially for commercial applications where cost is an important consideration. This work describes the performance, analysis, and design of the multisegment dielectric resonator antenna (MSDRA) element [7], which has been developed to enhance the amount of coupling from the microstrip line to the DRA. Although some rigorous numerical modeling has been carried out [8]–[9], the design and optimization of the MSDRA's have been achieved primarily through a combination of simple models and experimental optimization. A more thorough treatment of MSDRA's has been carried out and a methodology for designing these useful elements is presented in the following sections.

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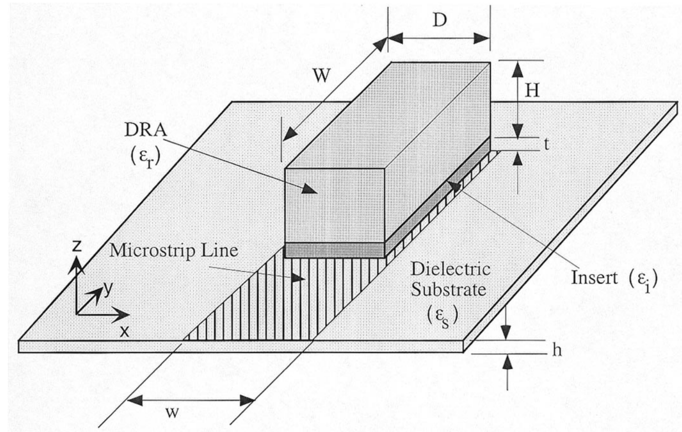

Fig. 1. The multisegment dielectric resonator antenna.

II. MSDRA AND THE MODIFIED DIELECTRIC WAVEGUIDE MODEL

The MSDRA configuration is shown in Fig. 1. It consists of a rectangular DRA of low permittivity under which one or more thin segments of different permittivity substrates are inserted. These inserts serve to transform the impedance of the DRA to that of the microstrip line by concentrating the fields underneath the DRA; this significantly improves the coupling performance [1], [8]. In general, more than one insert can be added to obtain the required impedance match, but to reduce the complexity of the fabrication process and ultimately the cost, it is desirable to use only a single insert. The radiation patterns of the MSDRA are similar to those of a simple rectangular DRA, which radiates like a short horizontal magnetic dipole. MSDRA's have been successfully used in linear and planar arrays at C, X, and Ku-bands [10]–[12].

Initial designs of the MSDRA involved a combination of a dielectric waveguide model for determining the DRA parameters, and experimental optimization to determine the insert parameters. The dimensions of the radiating portion of the MSDRA were determined using the equations developed for the dielectric waveguide model (DWM) for a rectangular resonator in free-space [13]

$$k_z \tan(k_z H) = \sqrt{(\varepsilon_r - 1)k_o^2 - k_z^2} \tag{1}$$

where

k_z	$\sqrt{\varepsilon_r k_o^2 - k_x^2 - k_y^2}$;
k_x	π/D;
k_y	π/W;
k_o	$2\pi f_o/c$;
c	3×10^8 m/s.

TABLE I
EFFECTS OF VARIOUS INSERTS ON MSDRA PARAMETERS

MSDRA	t (mm)	ε_i	ε_{eff}	f_{oe} (GHz) (Estimated)	f_{om} (GHz) (Measured)	% Error $(f_{om}-f_{oe})/f_{om}$	Max Return Loss (dB)	Loop Band-width
0	0	-	6.9	14.8	15.2	2.3%	6	21%
1	0.25	20	7.2	14.5	14.7	1.4%	8	18%
2	0.635	20	7.6	14.0	14.5	3.4%	9	18%
3	1.0	20	7.9	13.5	13.9	2.9%	17	16%
4	0.25	40	7.3	14.5	14.7	1.4%	8	20%
5	0.635	40	7.8	13.9	13.7	-1.5%	19	13%
6	1.0	40	8.3	13.2	12.9	-2.3%	16	5%
7	0.25	100	7.3	14.5	14.7	1.4%	8	16%
8	0.635	100	7.9	13.8	13.1	-5.3%	16	7%
9	1.0	100	8.5	13.0	10.8	-21%	14	5%

An expression for the radiation Q-factor is also given in [13], which can be used to estimate the bandwidth of the DRA. These simple equations are ideal for first-order designs and have been shown to predict the resonant frequency and radiation Q-factor with an accuracy ranging from 1 to 12%, depending on such factors as the aspect ratio, the relative permittivity, and the coupling method.

For the MSDRA, the permittivity and thickness of the insert will affect the resonant frequency, impedance bandwidth, and the coupling level. To determine these effects, a systematic study involving nine inserts for a Ku-band MSDRA using both experimental and numerical modeling was performed. The dimensions of the DRA (as defined in Fig. 1) fabricated from a ceramic material with $\varepsilon_r = 10$ were $W = 7.875$ mm, $H = 3.175$ mm, $D = 2$ mm. A 50 Ω feed line was used ($w = 1.9$ mm) which was printed on a substrate with thickness $h = 0.762$ mm and relative permittivity $\varepsilon_s = 3.0$. The thickness and permittivity of the nine inserts are listed in Table I. To account for the effect of the insert and substrate on the resonant frequency of the MSDRA, the DWM equations were modified by including an effective permittivity $(\varepsilon_{\rm eff})$ and effective height $(H_{\rm eff})$. Adopting a simple static capacitance model, the effective permittivity of the MSDRA was calculated using

$$\varepsilon_{\rm eff} = \frac{H_{\rm eff}}{H/\varepsilon_r + t/\varepsilon_i + h/\varepsilon_s} \tag{2}$$

where ε_r, ε_i, and ε_s are the permittivities of the DRA, insert, and substrate, respectively. The effective height $(H_{\rm eff})$ is simply the sum of the DRA height (H), insert thickness (t), and substrate thickness (h)

$$H_{\rm eff} = H + t + h. \tag{3}$$

Equations (2) and (3) were substituted into (1) with $\varepsilon_{\rm eff}$ replacing ε_r and $H_{\rm eff}$ replacing H. The effective permittivity $(\varepsilon_{\rm eff})$ and the resultant resonant frequency (f_{oe}) are listed in Table I.

III. EXPERIMENTAL CHARACTERIZATION OF THE MSDRA ELEMENTS

This investigation involved fabricating the nine MSDRA's along with the DRA without insert and measuring their return loss when fed by a microstrip line, as illustrated in Fig. 1. Each antenna was placed on top of the 50 Ω line with the edge of the MSDRA flush to the open end of the line. Although this location did not necessarily result in the maximum amount of coupling for each MSDRA, it was kept constant in order to study the effects of the insert parameters. The maximum return loss obtained for the fundamental mode of each case is listed in Table I. This value indicates the amount of power coupled from the microstrip line into the MSDRA. Without the insert (MSDRA 0), the maximum return loss for the lowest order mode was small (6 dB). With the various inserts, the return loss was improved to a maximum of 19 dB.

More insight can be obtained on the effects of the insert parameters by looking at the reflection coefficient in polar (Smith Chart) format. Fig. 2 shows the reflections coefficients for $\varepsilon_r = 20$ inserts (MSDRA's 1, 2, 3) along with MSDRA 0 (no insert). In this graph, the reflection coefficients have been normalized by the reflection coefficient of the 5-cm unloaded 50 Ω line, to remove the frequency dependent phase component of the line. In this polar plot, the resonance loop of MSDRA 0 (no insert) is located in the lower right quadrant, indicating that the antenna is overcoupled with a strong capacitive reactance. Increasing the insert thickness results in a reduction of the capacitive reactance, shifting the locus of the reflection coefficient toward the center of the Smith Chart. Reflection coefficient curves with similar trends were measured for the other cases. In Fig. 3, the thickness of the insert is kept constant at 0.635 mm, while the permittivity is varied. The amount of shift in the reflection coefficient curves is seen to be proportional to the insert permittivity. Table I lists the bandwidth of each loop and the resonant frequency (which, for this study, is calculated as the average of the frequencies at the beginning and end of the loop locus, as shown in Figs. 2 and 3). The inserts are seen to be acting as impedance transformers and can be used to match the impedance of the DRA to that of the microstrip line. By optimizing the permittivity and thickness of the insert, the DRA can be matched to the microstrip feed line while still maintaining a wide impedance bandwidth. As mentioned earlier, a further improvement in the match is possible by adjusting the position of the MSDRA with respect to the open end of the microstrip line. This

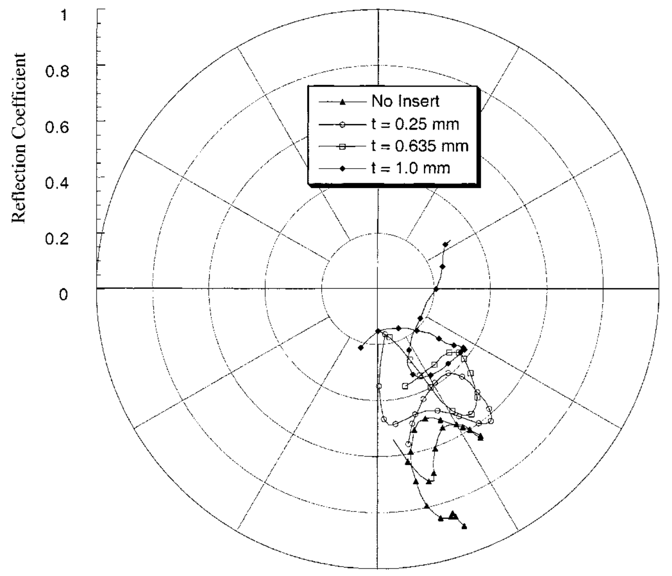

Fig. 2. Effect of increasing insert thickness on the MSDRA reflection coefficient.

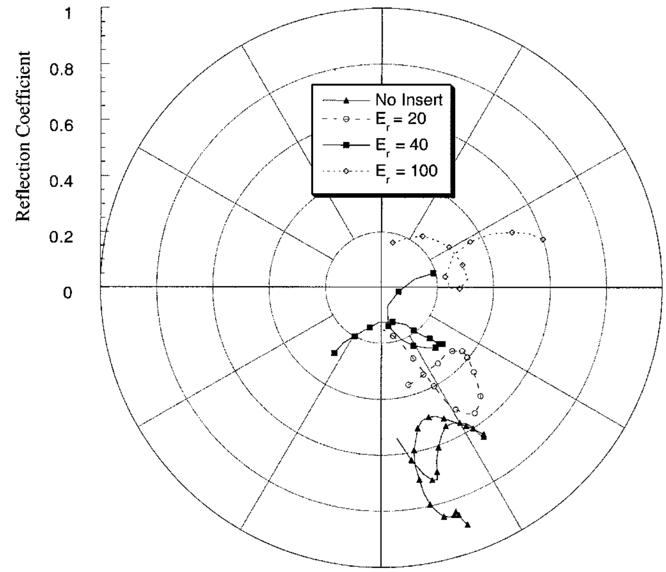

Fig. 3. Effect of increasing insert permittivity on the MSDRA reflection coefficient.

is very convenient, since the matching can be done without introducing an external matching network which would increase real-estate and add to the cost and complexity of the antenna.

The modified DWM equations were used to predict the resonant frequency of the MSDRA's. In order to estimate the amount of coupling between the microstrip line and the MSDRA and ultimately the input impedance of the MSDRA, a more rigorous approach was required. The geometry was analyzed using two time-domain numerical techniques: the transmission line matrix (TLM) method and the finite-difference time-domain (FDTD) method. The ten cases listed in Table I were independently modeled using both the TLM and FDTD methods. A comparison was made of the simulated versus measured return loss for each case. Fig. 4 shows the return loss of a typical case (MSDRA2 in Table I). The simulated coupling levels are typically within a few decibels of the measured values while the predicted location of the resonance frequencies are within a few percent. The measured trends shown in Figs. 2 and 3 are also predicted using these numerical methods. The discrepancies between the measured and simulated results may be attributed to the challenge of accurately modeling structures with highly concentrated fields confined in a small region of the geometry. Better agreement might be achieved by using a more suitable discritization and nonuniform mesh (which was unavailable with the in-house codes that were used) [9]. Nevertheless, these numerical methods are a useful tool in predicting the input impedance of the MSDRA's.

IV. Design Guidelines

The data in Table I, indicates that inserts with permittivities of either 20, 40, or 100 can be used to achieve good coupling between the microstrip line and the DRA. By interpolation, the correct combination of insert permittivity and thickness can be used as a transformation layer to achieve maximum coupling. There are two considerations to keep in mind when choosing

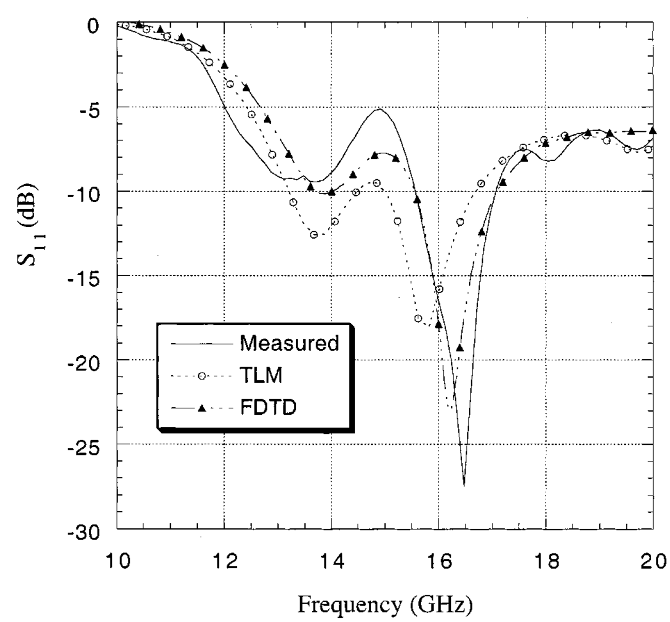

Fig. 4. Comparison between measured and simulated MSDRA reflection coefficient.

these values. The first is to ensure that the insert itself does not radiate. In Table II, the DWM equations were used to estimate the resonant frequency (f_{oe}) of the inserts as if they were to be used as DRA's. For three of the inserts (numbers 6, 8, and 9), the resonant frequency falls within the range of the MSDRA. It is undesirable to use these inserts in the MSDRA configuration since they will themselves behave as radiating elements and not as an effective impedance transformer. A second consideration is the impedance bandwidth obtained by the various inserts. In general, the higher the insert permittivity, the narrower the impedance bandwidth, for a given insert thickness. MSDRA's with higher permittivity inserts also show a greater sensitivity to their position with respect to the open end of the microstrip line. Since one of the objectives of using the MSDRA is to obtain a wide impedance bandwidth, the insert permittivity should be chosen accordingly. This places an upper bound on permittivity. From Table I, it appears that the optimal insert parameters correspond to MSDRA 3 or MSDRA 5. An insert of permittivity 20 and a thickness of 1.0 mm achieves similar results to an insert of permittivity 40 with a thickness of 0.635 mm. The optimum coupling can thus be thought of as a function of an "effective insert thickness" (t_{eff}) where $t_{\text{eff}} = t\sqrt{\varepsilon_i}$. This gives the designer a degree of flexibility in choosing the physical insert thickness and permittivity for optimal coupling.

Based on the above measurements as well as on measurements carried out on MSDRA's designed for frequencies at C- and X-band, the following procedure has been established for designing MSDRA's.

1) Determine the dimensions (L, W, H) of the DRA using the DWM equations for the desired resonant frequency, radiation Q-factor (for estimating the expected bandwidth), and the location of higher-order modes (to ensure they are far enough away not to add to the cross-polarization levels inherent in the desired mode). The permittivity of the DRA should be chosen to be between 6 and 12, for wide-band operation.
2) Chose an insert permittivity between 20–40 and an insert thickness (t) such that $0.1 < T < 0.3$ [where $T = t/(t + H)$].
3) Estimate the resonant frequency of this MSDRA structure by using the DWM equations with the effective permittivity (ε_{eff}) and effective height (H_{eff}) based on the insert parameters chosen in 2. The insert parameters or the DRA dimensions might require some adjustment if there is a significant shift in the desired resonant frequency.
4) Once fabricated, some experimental optimization may be required to maximize the coupling. The simplest form of optimization is done by adjusting the position of the MSDRA with respect to the open end of the microstrip line. If this is not sufficient, a second iteration of the MSDRA parameters may be required.

TABLE II
ESTIMATED RESONANCE OF INSERT SEGMENTS

Insert	t (mm)	ε_i	f_{oe} (GHz) (Estimated)
1	0.25	20	68
2	0.635	20	29
3	1.0	20	20.3
4	0.25	40	48
5	0.635	40	20.7
6	1.0	40	14.0
7	0.25	100	31.2
8	0.635	100	13.0
9	1.0	100	10.0

V. SUMMARY

Wide-band performance, low loss, and design flexibility are some of the features which make DRA's attractive candidates as elements in low-profile arrays. Until recently, it has been difficult to achieve wide-band coupling between a microstrip line and a single DRA. Such a configuration is desirable to make the integration of DRA's with printed technology more amenable. The development of the MSDRA greatly facilitates this integration, thus paving the way for array development. The work presented in this paper was carried out to deepen the understanding of MSDRA's and to provide assistance in their analysis and design. The effects of varying the insert thickness and material permittivity were examined. The MSDRA insert behaves like an impedance transformer, matching the impedance of the DRA to that of the microstrip line. The amount of coupling can be controlled by varying the insert parameters and with the appropriate combination, the coupling level, and impedance bandwidth can be optimized. Simple equations were presented to predict resonant frequency, and guidelines were provided for the design of MSDRA's. In order to predict the coupling behavior, numerical methods were used to model the MSDRA. These methods were also used to predict the general trends in the coupling response, with a variation in either the insert thickness or material permittivity. It should be noted that although this paper was limited to examining the specific example of a Ku-band MSDRA fed by a 50-Ω line, the principle is not restricted to this case. Similar trends would be obtained for MSDRA's at other frequency bands fed with microstrip lines of arbitrary impedance values.

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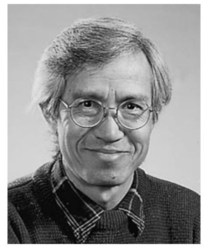

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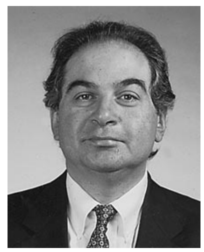

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