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LOW-LOSS COUPLING TO DIELECTRIC RESONATORS

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Introduction

Many microwave systems require high- Q resonant elements for their realization. Microwave and mm-wave resonators were for many years fabricated from lengths of shorted transmission line or waveguide. More recently, practical dielectric resonator (DR) elements have been developed which exhibit high Q s, and are in some aspects superior to waveguide resonators [1]. The DR is well suited to hybrid microwave integrated circuit (MIC) fabrication and MIC s utilizing DR s have significant size and weight advantages relative to waveguide versions of the same circuits.

The work reported here is concerned with the utilization of DR s in applications where minimum loss is critically important, such as bandpass filters. In these applications, it is desirable that the unloaded Q (Q_u) of a DR be preserved under load, since Q_u degradation translates into added dissipative loss. Q_u is determined primarily by the dielectric loss of the DR element and secondarily by conduction losses occurring when lossy conductors such as enclosure walls or coupling structures are located near the DR . Even relatively good conductors like aluminum cause significant degradation in Q_u when located less than one DR diameter away from the circumferential, or one thickness away from the flat surfaces

of the DR [2]. These losses are generally attributed to eddy currents induced in the lossy conductors. The role of the coupling structure used to couple into and out of a DR in degrading Qu has received little attention; however, tight coupling between a DR and a microstrip transmission line can severely degrade Qu [3,4]. This work reports the results of experimental studies of various coupling methods. A number of recommendations for optimizing DR -microstrip coupling are made. A coupling method is described which causes less Qu degradation with tight coupling than microstrip- DR coupling. These experiments were conducted in the C-band region and used Trans-Tech Inc. D-8515.500.200 DR elements. Manufacturers data and our own measurements indicate that when conduction losses are minimized, the unloaded Q of these elements exceeds 10,000.

The interaction between a DR and a microstrip line is fundamentally a fields problem; however, a rigorous fields analysis using numerical methods is inflexible and difficult. This paper attempts to explain the observed coupling phenomena in terms of basic field and circuit concepts.

Coupling Methods

The method generally used for coupling into a DR operating in a microstrip environment is shown in Figure 1A. The DR is located adjacent to a point that would be a current maximum on an isolated open-circuited microstrip transmission line, with the degree of coupling controlled by the lateral displacement of the DR from the line [1]. Coupling is largely magnetic, since the E -field of the microstrip line at the coupling plane is small in magnitude and orthogonal to that of the $DR TE_{01\delta}$ mode. Configuration 1B uses a short-circuited coupling line with the DR located a half-wavelength back from the discontinuity. Although these two schemes might appear to be equivalent, it has been observed that when open-circuited coupling lines are used in a 2-port circuit, such as a bandpass filter, there is significantly more direct coupling between the ports than is seen with short-circuited coupling lines. This leads to degraded out-of-band rejection in a filter. This effect is attributed to

the fact that open-circuited microstrip lines radiate much more than an equivalent short-circuited line, especially in thick, low-epsilon substrates [5,6]. Configuration 1C is essentially a stripline version of 1B.

Experimental Results

The configurations in Figure 1 were investigated experimentally to evaluate their performance in applications requiring tight coupling and low loss. The loaded Q (Q_L) and Q_u were measured by the Q -circle technique [7] as the coupling to the DR was varied, and plotted in Figure 2. The coupling factor β is defined as

$$\beta = (Q_u/Q_L) - 1 \quad (1)$$

and can be computed from Q_u and Q_L or measured directly from the Q -circle Smith-chart overlay [7]. Beta versus Q_L is plotted in Figure 3. The following conclusions were drawn from these experiments which can be summarized with the aid of Figures 2 through 7.

(1) In Figure 2, Q_u decreased monotonically with increased coupling. This was initially attributed solely to increased eddy-current loss as the DR was moved closer to the line. However, it was subsequently determined that any dissipative loss in the coupling-line circuit become increasingly important as coupling increases. This is demonstrated by cases 1 and 2, which differed only in the Q -factors of the coupling lines (500 vs. 200). The difference was attributed to poor fabrication which caused excess loss in the ground plane/case/connector interface.

(2) There is a configuration-dependent upper limit on β in microstrip- DR coupling which occurs with the DR partially overlaying the line and separated from the line (as with a low-epsilon dielectric spacer) to prevent suppression of the $TE_{01\delta}$ mode. This orientation roughly corresponds to lateral alignment of the points of maximum H -field intensity in the $DR TE_{01\delta}$ mode, which occurs somewhat inside the perimeter of the DR [9], and maximum current density at the edges of the microstrip line. This effect is illustrated in Figures 5 and

6. As the point of maximum coupling is passed, Q_L begins to increase with decreasing d , but the corresponding Qu is lower because of increased eddy-current loss. While the “turn-around” point is not so obvious in the 4 mil case in Figure 5, it can be seen that the curve does not reach the $\beta = 60$ locus. In the stripline case, Figure 1C, β_{\max} occurred with the DR touching the blade ($d = 0$).

(3) An air gap or low-dielectric spacer between the DR and substrate can either increase [10] or decrease β , depending on the geometry, as there are two competing mechanisms at work: increasing s raises the in-situ Qu by lowering eddy-current loss, but can either decrease or increase the magnetic field intensity (H) at the DR . The latter is illustrated in Figure 4, which is a sketch of the H -fields of an open and a shielded microstrip line. In both cases, moving up from the substrate along line A (tight coupling) reduces the magnetic field intensity; whereas, moving upward along line B (loose coupling), there is initially an increase in H . Based on these experiments and arguments, it is concluded that β will always initially increase with s when coupling is loose since both Qu and H increase with s ; with tight coupling, the increase in Qu initially outweighs the decrease in H , and β_{\max} occurs with a nonzero value of s , as shown by cases 1 and 4 in Figure 3. Figure 5 provides additional evidence of β -enhancement with s in both coupling regimes. In every case, using a thinner spacer and a larger value of d to obtain a given Q_L resulted in a lower Qu . An additional point with practical implications, not obvious from Figure 5, is that the sensitivity of Q_L to d is minimum at the point of maximum coupling, as illustrated in Figure 6. Thus, the largest s comensurate with the required Q_L will maximize Qu and desensitize Q_L and β to d .

(4) Maximum β and minimum Q_L are not always coincident, as demonstrated by case 2 in Figures 2 and 3. This behavior is associated with very small values of s , which result in large eddy-current loss when the DR is in the region of β_{\max} described in (2). Q_L can be reduced further by moving the DR more onto the line, past the point of β_{\max} , but more dissipative

loss is introduced, and Qu is reduced. Thus, Q_L is reduced at the expense of Qu , rather than an increase in the magnetic coupling. This can be seen by rewriting (1) as

$$Q_L = Qu/(\beta + 1) \quad (2)$$

This operating regime should be avoided when dissipation loss must be minimized.

(5) Increasing Z_o decreases coupling, that is, tight coupling dictates a low- Z coupling line. Figure 7 compares a 120 Ohm coupling line ($w = 10$ mils) with a 50 Ohm line ($w = 90$ mils) in otherwise identical fixtures, driven from a 50 Ohm source. The high- Z line had a much lower β_{\max} and was in every aspect inferior to the matched line. Any decrease in eddy-current loss in the 10 mil line, due to its smaller size, was more than offset by the higher Qu [11] and greatly increased β_{\max} of the 90 mil line.

The larger β_{\max} on the matched line was surmised to be a result of several factors. At 4 GHz, the Q -factors of 50 and 120 Ohm lines on 31 mil Duroid are 400 and 295 [11], respectively. Lower line- Q was observed to reduce Qu which, by (1), reduces β . Additionally, the lower- Z line had a larger value of current-maximum on the line, which produced a stronger H -field in the region of the DR . The current phasor on a doubly-mismatched transmission line is given by [12],

$$I(x) = \frac{V_g(e^{-\gamma x} - \Gamma_L e^{-2\gamma\ell} e^{\gamma x})}{(R_g + Z_o)(1 - \Gamma_g \Gamma_L e^{-2\gamma\ell})} \quad (3)$$

where ℓ is the total line length and x is the distance between the input and the coupling planes. In a source-matched system, $Z_o = R_g$, and $\Gamma_g = 0$. The maximum current on the line occurs when x and ℓ are such that the traveling waves in (3) are in-phase, and is

$$I_{\max} = \frac{V_g}{(R_g + Z_o)} [1 + |\Gamma_L|] \quad (4)$$

neglecting loss. In this experiment, Γ_L was -1 ($Z_L = 0$) and (4) reduces to $I_{\max} = V_g/Z_o = V_g/R_g$, regardless of whether x is an odd or an even multiple of $\lambda/4$.

The high- Z line ($Z_o > R_g$) presented a mismatch to the source resistance, and I_{\max} was affected by the dimension x , which was approximately 180 electrical degrees in the test

fixture. Evaluating (3) for this case gives $I_{\max} = V_g/Z_0$; the high- Z line therefore reduced I_{\max} by the factor 0.417, or 50/120. However, the observed reduction in β_{\max} with the high- Z line, shown in Figure 7, was by a factor of 0.187 (11.5/61.5), which is considerably more than can be justified by the above arguments. As an afterthought, it is noted that if the high- Z line had been made 90 degrees longer, I_{\max} would have increased to V_g/R_g , corresponding to the maximum generator current.

(6) Conf. 1C practically eliminated Qu -degradation due to ground plane eddy-current loss with the 0.25 ins dielectric spacer, although increased loss from the coupling line is apparent with tight coupling, as demonstrated by Figure 2, case 5.

In the interest of further reducing coupling structure losses, other coupling schemes were investigated. The " L -probe" shown in Figure 8 has been used in cavity applications [13], and is adaptable to microstrip. This configuration was found to exhibit significantly less tight-coupling loss than microstrip- DR coupling and had the additional practical advantage that the degree of coupling could be varied over wide ranges by changing the coupling angle θ_c , rather than moving the DR . While the arrangements previously considered here were for application to multi-section filters, the L -probe was originally evaluated for use in a reflection oscillator involving only a single DR . However, the concept seems adaptable to hybrid MIC applications involving multiple DR elements.

In Figure 8, the DR is mounted on a low-loss Rexolite spacer in the center of a cylindrical cavity. The L -probe is formed by extending the center conductor of a coaxial line passing through an end wall of the cavity into the cavity and bending it at a 90 degree angle. The angle θ_c is a critical parameter, as may be seen in Figure 9. Maximum coupling with the longer probe arms occurs when the probe end is nearly touching the DR , and θ_c is between 25 and 30 degrees. Qu versus Q_L is plotted in Figure 2 for two of the four L -probe parameter sets of Figure 9, which collectively yielded a 40:1 range in Q_L ; a 10:1 Q_L range was obtained with one parameter set. In sharp contrast to the other curves in Figure 2, increased coupling with the L -probe does not significantly lower Qu . The tightest coupling that was

obtained with the parameters of Figures 8 and 9 resulted in a β_{\max} of 51.7 ($Q_L = 165$ and $Qu = 8,700$). The maximum Qu for the cavity- DR combination exclusive of L -probe loss was about 9,000 for an aluminum cavity; silver-plating the cavity increased Qu to about 10,000. Thus, tight-coupling loss is seen to be insignificant with the L -probe. Beta vs. Q_L for the L -probe is plotted in Figure 3 for comparison with the other configurations. No indication of a β_{\max} suggests that moving the probe closer to the DR might yield tighter coupling. More experimental work is needed here.

The excellent results obtained with the L -probe are thought to be due to a closer match between the field patterns of the probe and the $DR TE_{01\delta}$ mode. As noted earlier, only the H -fields are in alignment at the coupling plane with the usual microstrip coupling. Non-alignment of the E -fields results in field pattern distortions, especially under tight coupling conditions, and the introduction of ohmic losses. The L -probe is believed to have both a substantial E -field component in rough alignment with the circumferential E -field of the DR , and a compatible H -field component when the arm length, in Figure 8, approaches a quarter wavelength. At the angle of maximum coupling ($\theta_c = 25\text{--}30$ degrees) the probe arm approaches orthogonality to the $DR E$ -field, and therefore lies roughly along a line of low gradient, since the $TE_{01\delta}$ mode has no radial E -field components.

Conclusions

Based on the experimental observations and arguments presented here, the following conclusions were drawn about coupling to DR elements:

- (1) There is a configuration-dependent upper limit on the degree of coupling that can be achieved. With the low-epsilon substrate materials used here, $\beta_{\max} < 65$.
- (2) Tight coupling between a DR and a microstrip line causes Qu degradation, and therefore increased dissipation loss.

- (3) Q_u degradation can be reduced by (a) using a low- Z coupling line, (b) using an air-gap between the DR and the substrate and (c) maintaining the highest possible Q in the coupling line.
- (4) The L -probe configuration exhibits much less coupling loss than microstrip- DR coupling for equal values of Q_L .
- (5) The degree of coupling between an L -probe and a DR can be varied over a wide range by changing the coupling angle between the probe arm and the DR .

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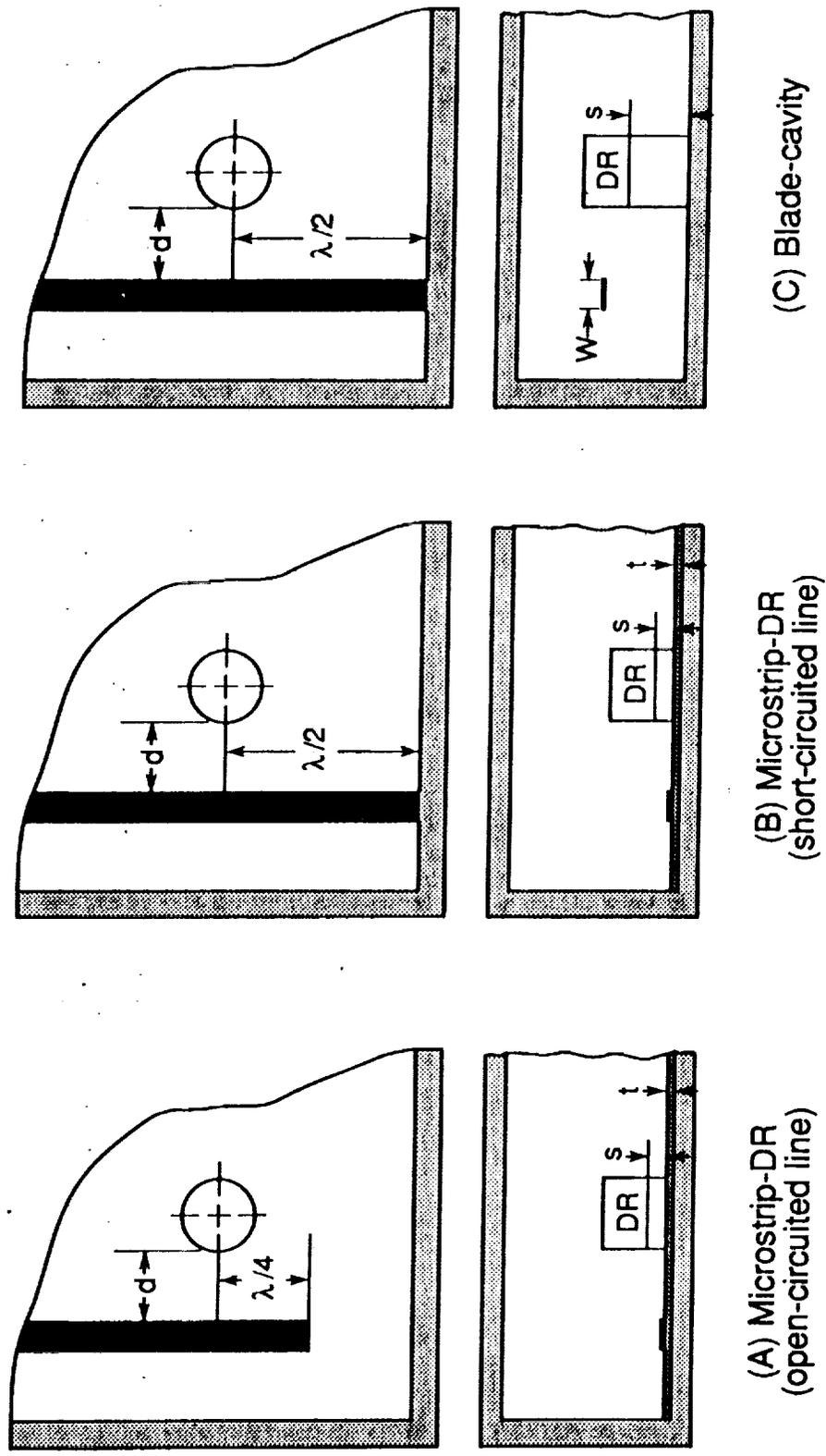


Figure 1.-H-field coupling methods.

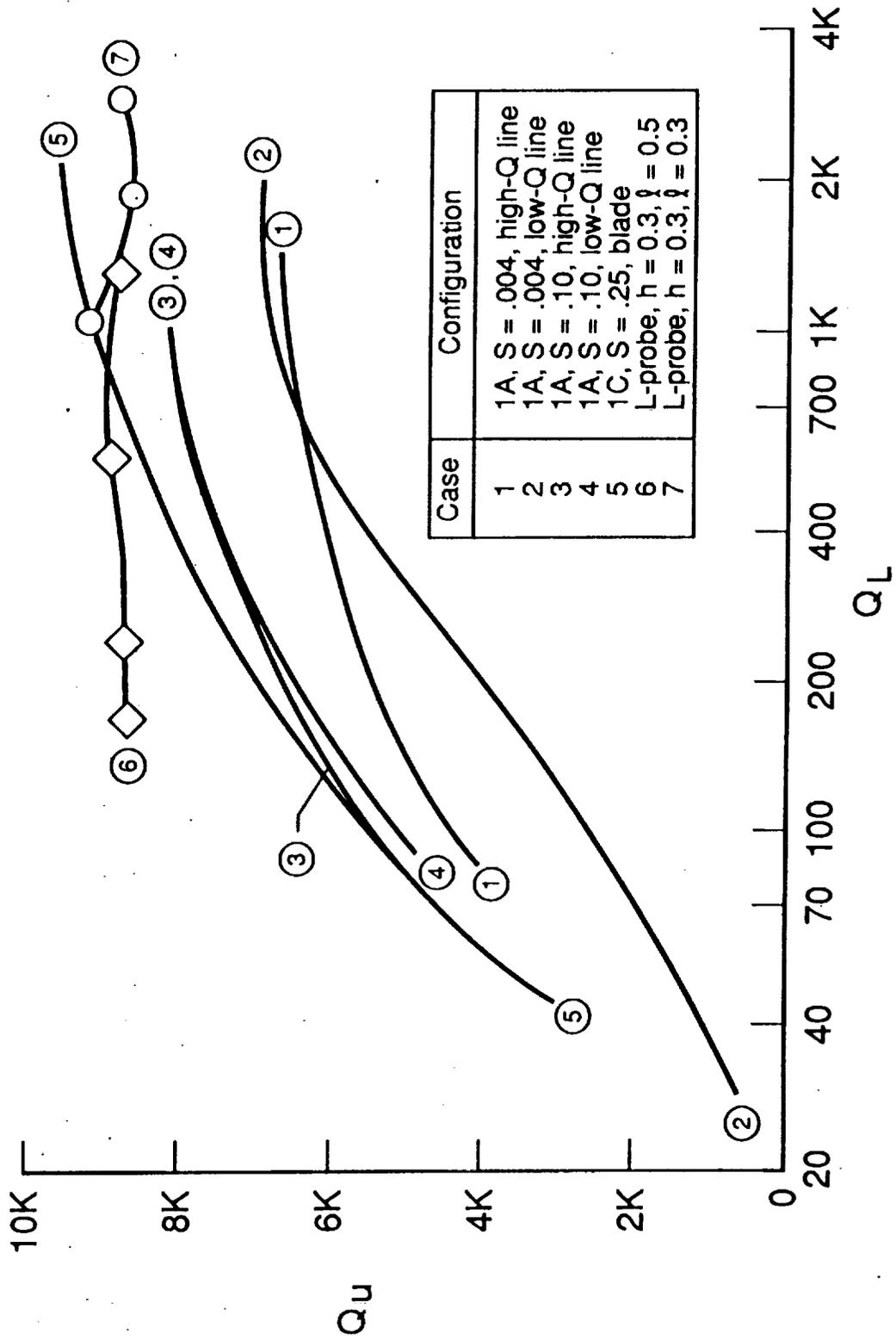


Figure 2.-Unloaded Q vs. loaded Q for various coupling configurations.

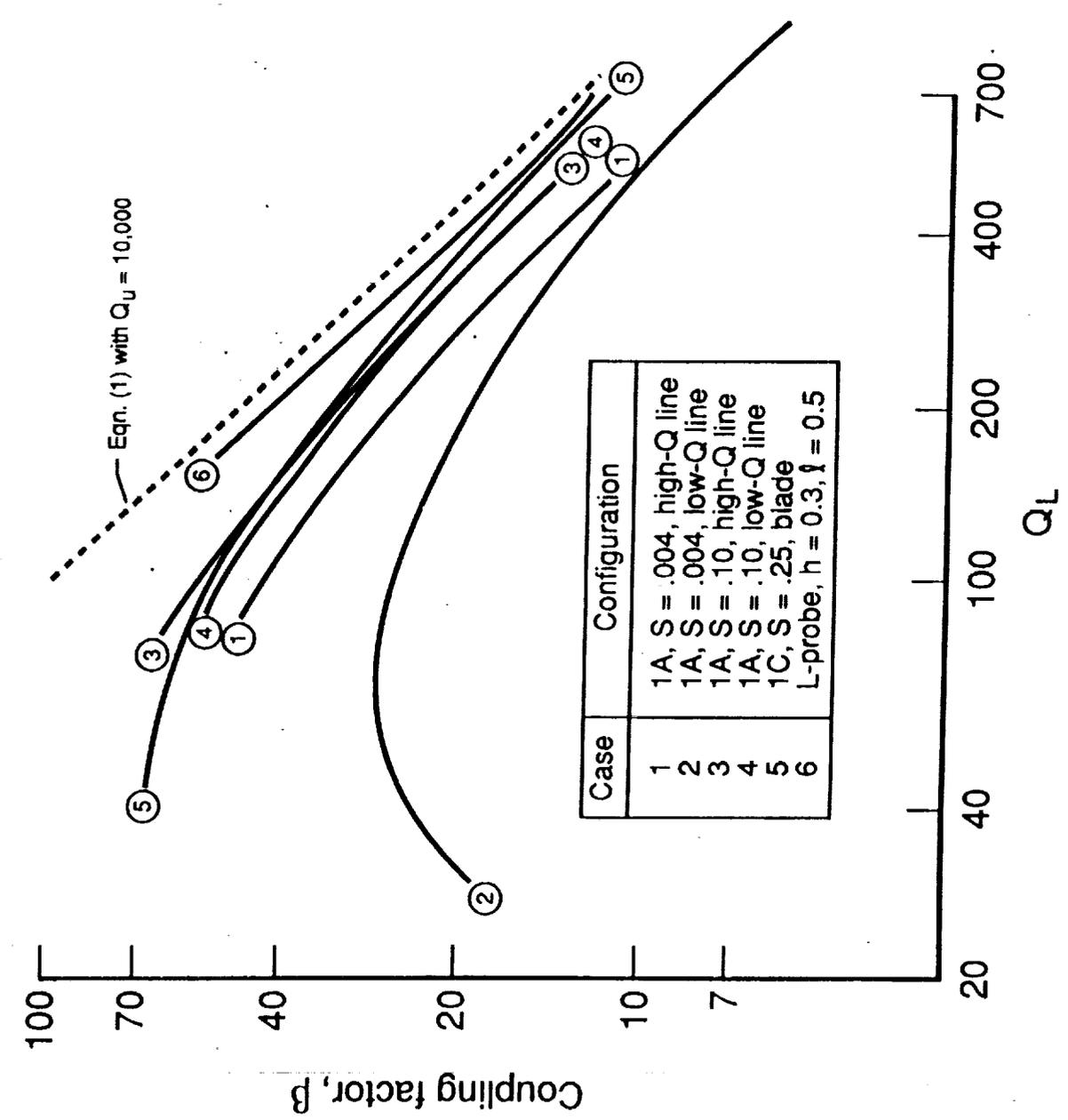


Figure 3.-Coupling factor vs. loaded Q for experimental configurations.

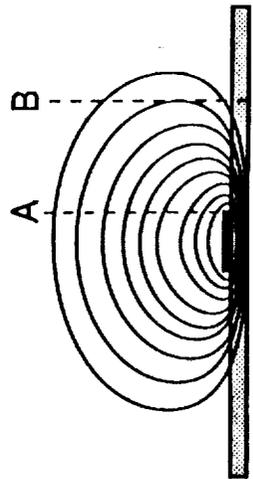
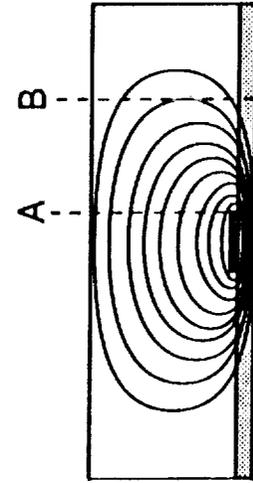


Figure 4.-Sketch of H-fields around open and shielded microstrip lines.

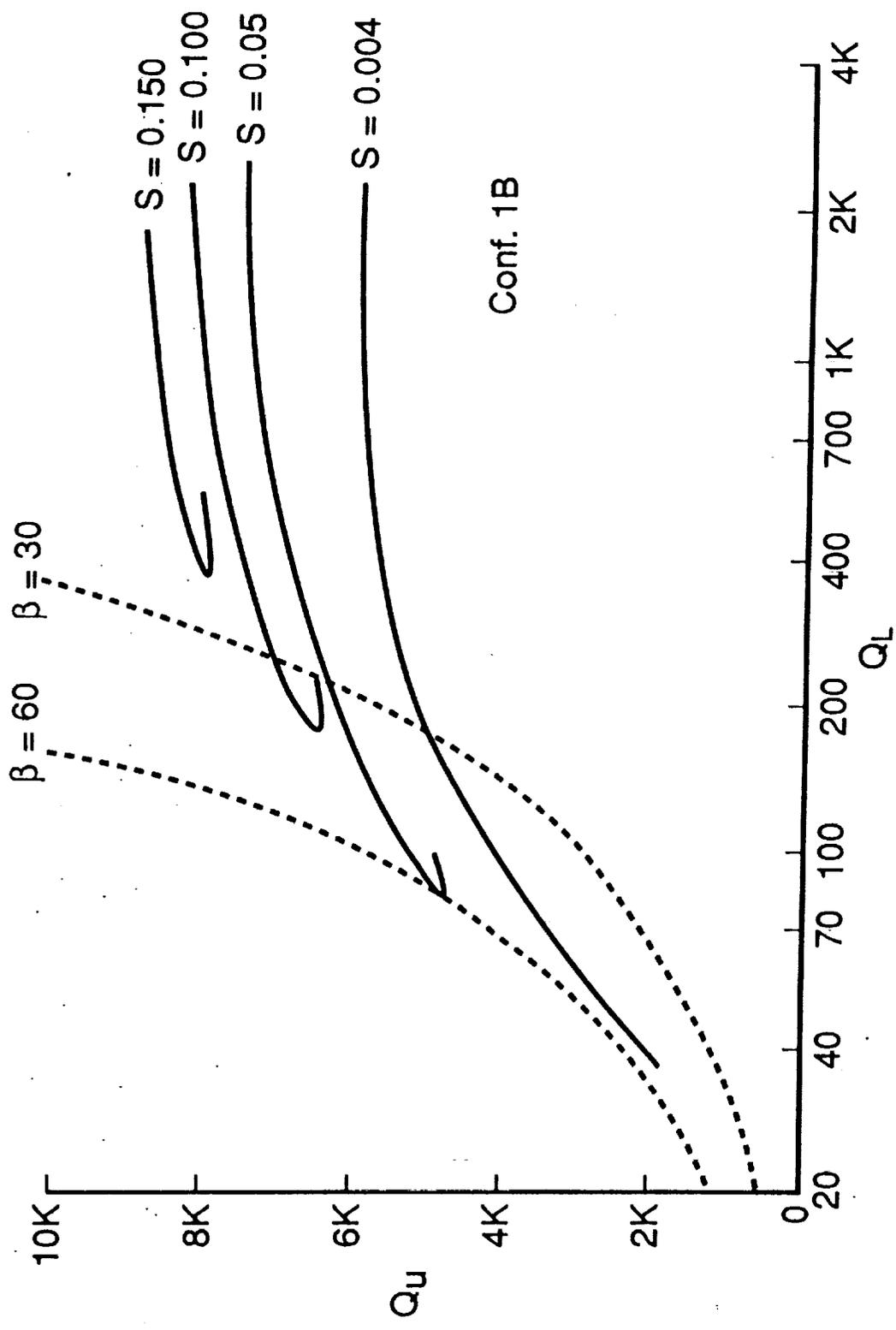


Figure 5.-Unloaded Q vs. loaded Q for various spacer thicknesses.

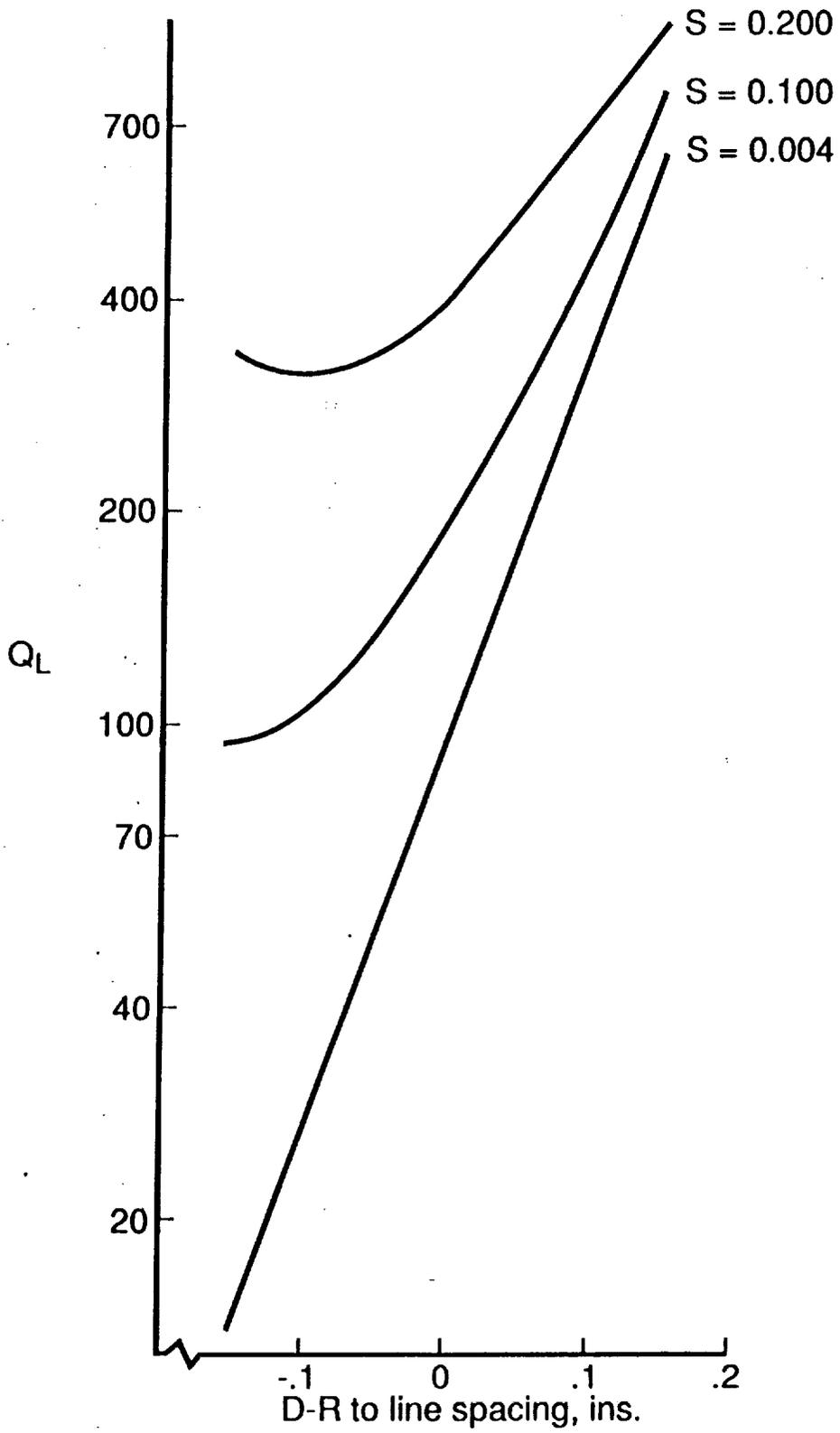


Figure 6.-Effect of spacers on loaded Q.

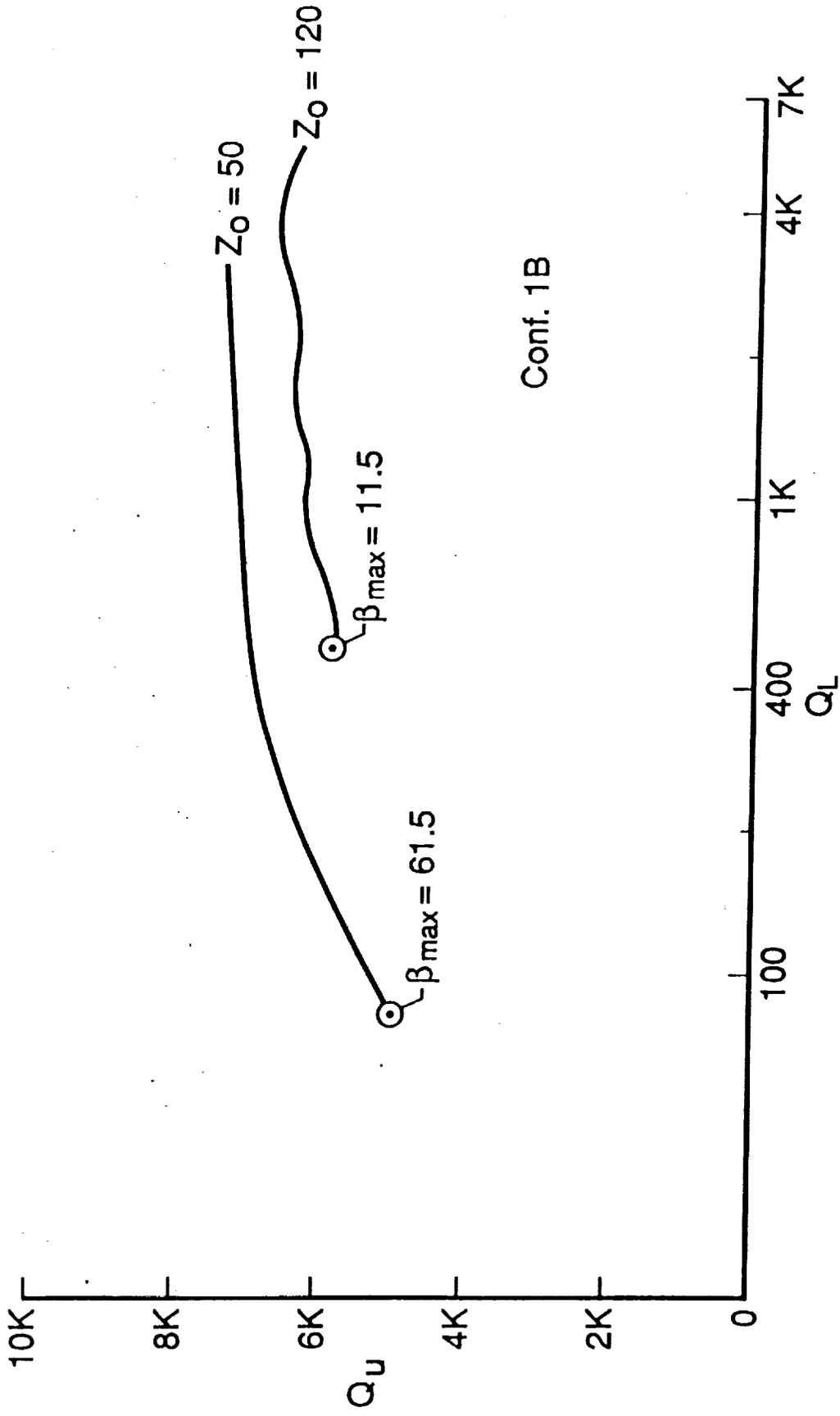


Figure 7.-Unloaded Q vs. loaded Q for source matched and mismatched coupling lines.

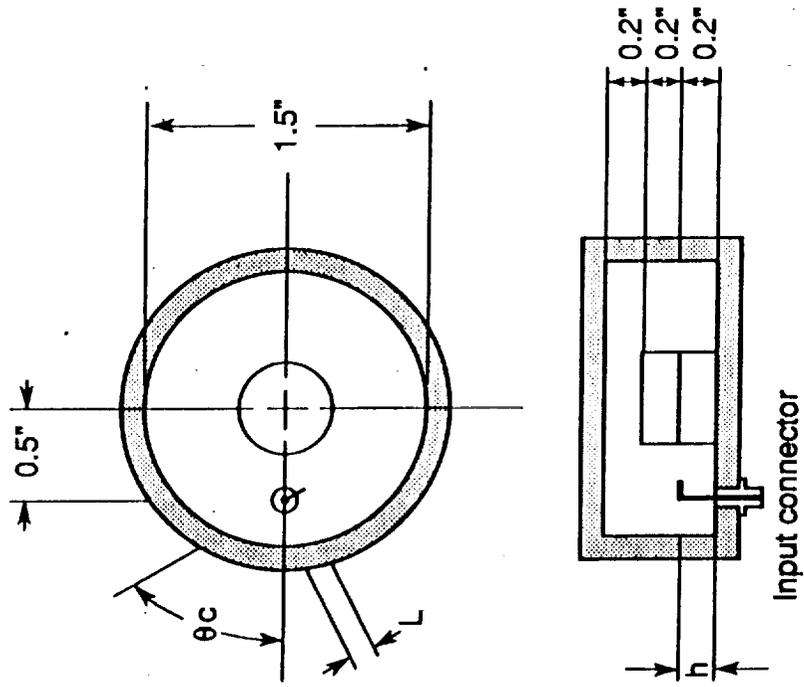


Figure 8.-L-probe coupling configuration.

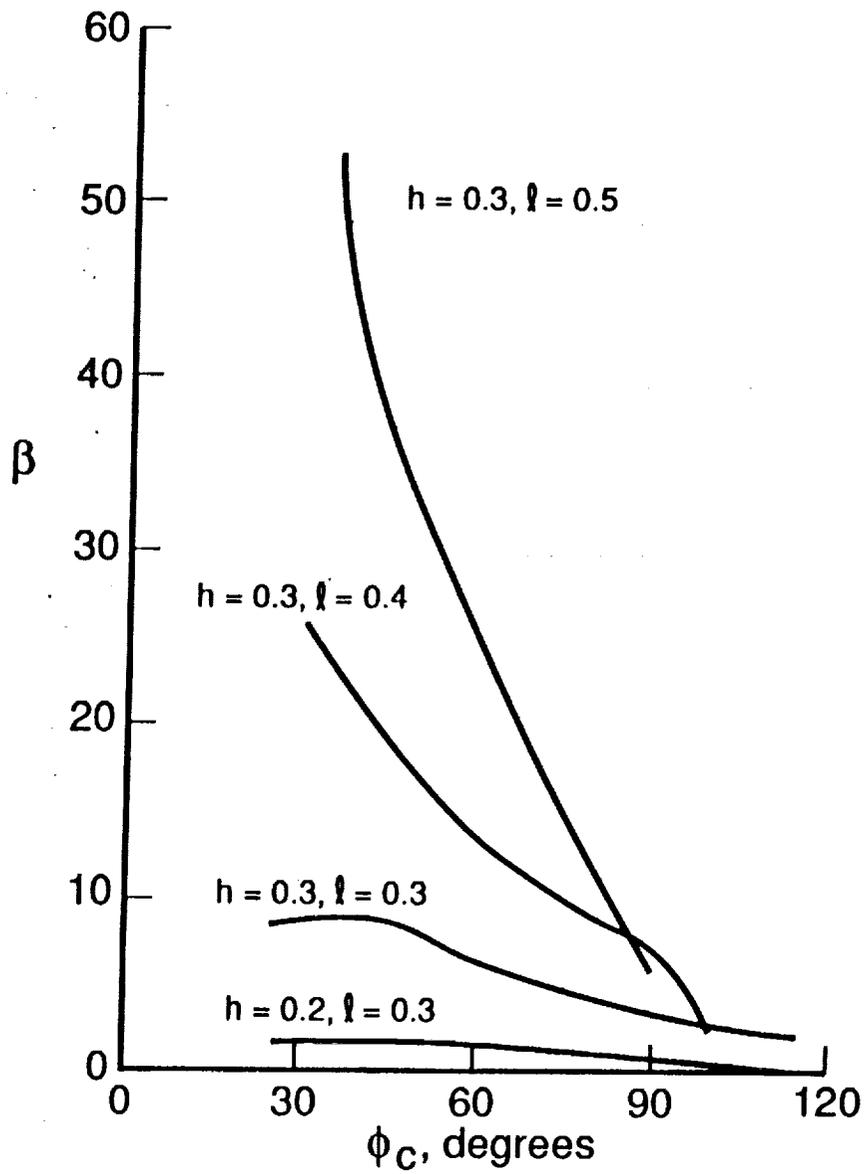


Figure 9.-Coupling factor vs. coupling angle for the Inverted-L configuration.



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16. Abstract This paper is a compilation of experimental observations and arguments concerning the use of dielectric resonators in applications requiring both tight coupling ($\beta > 10$) and high unloaded Q , such as low-loss bandpass filters. The microstrip-coupled dielectric resonator is the primary focus, but an alternative coupling technique is discussed and comparatively evaluated. It is concluded that coupling factors as large as 65 are achievable.					
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