Effect of Thin-Film Bi_2O_3 Overlay on the Quality Factor of a Microstrip Resonator

R. N. KAREKAR AND
MADAN K. PANDE, MEMBER, IEEE

***Abstract*—The effect of thin-film Bi_2O_3 overlay on a microstrip resonator has been studied. An improvement in Q suggests that lower radiation loss may be achieved in this manner.**

I. Introduction

Open microstrip resonators are often employed in microwave-integrated-circuit (MIC) techniques as, for example, in filters. One form is the standard half-wave resonator, open circuit at both ends, and coupled over a quarter-wavelength with the main transmission line. The total Q of a microstripline resonator is affected by the conductor loss, dielectric loss, and the radiation loss [1]–[3]. The microstrip is a mixed dielectric system in which a fair amount of the electric field exists in the air above the dielectric interface. In the design of coupled microstrip structures the odd-mode impedance value is often used [4] for arriving at the coupling and geometry. Unfortunately, a considerable portion of the odd-mode field exists in the air [5], which leads to fringing fields and radiative losses, particularly in open-circuit resonators. The overlay technique, in which a material of high dielectric constant [6]–[8] is placed over the circuit, has been one of the solutions to achieve higher directivity and higher coupling in microstrip couplers. For a machined alumina overlay, which is stuck on the microstrip circuits on alumina, a detailed analysis has been made by Spielman [7]. It may also be noted that Weirather [5] uses a thin-film nichrome overlay of 10 Ω/sq over one of the lines in the coupled region to achieve higher directivity by terminating the odd-mode field.

II. Thin-Film Approach

The thin-film approach in hybrid MIC's is not very compatible with sticking on machined pieces of high-dielectric-constant materials [6]–[8]. Since the primary cause of lower Q of a microstrip resonator is the radiation caused by the portion of the field in air, it would be logical to deposit a dielectric material as overlay on the microstrip circuit which would reduce radiation loss and cross coupling. In the thin-film technique it could be done as a part of the process flow, using mechanical or photolithographic masking as required. A survey of high-dielectric-constant materials shows [9] that $BaTiO_3$, TiO_2, and Ta_2O_5 are promising materials for overlay. A limited study conducted at our laboratory [10] on semimetal oxides shows that Bi_2O_3 can also be a useful material, with a dielectric constant of 32 and $\tan \delta = 0.01$ at 1 MHz and a dc resistivity of 10^{12} Ω/sq [11]. Bismuth oxide can be formed by heating an evaporated bismuth film in atmosphere, and can be easily etched (e.g., by HCl, $FeCl_3$). To investigate the feasibility of thin-film dielectric overlay, a study was conducted on a rejection filter at X band, consisting of a single half-wave open-circuited resonator, coupled over a quarter-wavelength. The behavior of a single microstrip line under the same conditions was also studied. The measurements of Q of the resonator and the characteristic impedance of the line and its variation with overlay can be used to study the effect of the thin-film overlay. The investigation reported here is a part of a Ph.D. program, taken in hand with a view to study the effect of thin-film overlay on coupling, isolation, and radiation loss in microstrip circuits.

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The authors are with the Department of Physics, University of Poona, Poona, India.

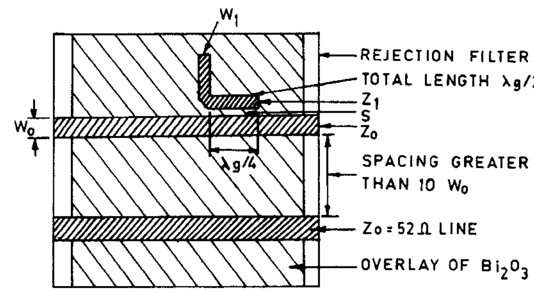

Fig. 1. Sketch of the rejection filter and single microstrip (post-etched geometry of filter $W_0 = 0.058$ cm, $W_1 = 0.066$ cm, $S = 0.073$ cm, $H = 0.0635$ cm).

III. Experimental Method

Plain alumina substrates 1 × 1 × 0.025 in were vacuum deposited with a chromium layer of 250 Å followed by about 700 Å of gold at 2 × 10^{-5} torr. Gold films were electroplated in a neutral cyanide bath (pH:7) to build up two skin depths. The required number of substrates were processed in a single batch. A rejection filter and a single microstrip line (Fig. 1) were photolithographically delineated on these metallized substrates, using the same negative and identical processing. The geometry was arrived at by using the standard tables and curves of Wheeler [12] and Bryant and Weiss [13]. The design parameters for $\lambda/2$ O.C. resonant single section maximally flat without overlay were $f_{0w} = 9.4$ GHz with 2-percent bandwidth, which gives $Z_{0e} = 1.14$. However, the design was experimentally optimized by removing the impedance discontinuity in the main line in an attempt to approach the filter design used by Johnson [14]. Next, the circuit faces of the substrates were deposited with bismuth. The substrate holder was designed to mask about a 30-mil contact area on each line. The bismuth layer was oxidized by heating in atmosphere in a temperature-controlled oven at 200° C for about 1 h. Lemon-yellow-colored Bi_2O_3 layers were obtained [11]. The thickness of the oxide layer was gradually increased by repeated evaporation and oxidation of bismuth. The thickness of the bismuth films were measured by Fizeau's step method, and the thickness of the oxide layer calculated using the volumetric expansion factor [15]. For circuit evaluation the microstrip circuits were mounted in a resilient-contact MIC test fixture, developed by the design wing of HAL Hyderabad, India. The performance evaluation of the rejection filter was done using a Hewlett-Packard X-band sweep setup, and Q was measured from half-power point bandwidth using HP X382A attenuator and HP532 B frequency meter. The straight-line impedance was evaluated approximately, using a (dc–12 GHz) Hewlett-Packard time-domain reflectometer (TDR) system.

IV. Results and Discussion

The variation of normalized Q, f_0, and I_L (insertion loss) versus thickness of Bi_2O_3 overlay is presented in Fig. 2. The variation of Z_0 with thickness of Bi_2O_3 overlay for the single microstrip line obtained from TDR measurements is also shown in the same figure. It can be seen that the Q of the rejection filter has increased with the Bi_2O_3 overlay thickness, particularly after 3000 Å. It is evident that there is a very small relative variation (1 percent at maximum) in the center frequency (f_0) for the overlay thickness range investigated. There is a marginal increase in the insertion loss, but its rate of increase up to the thickness of

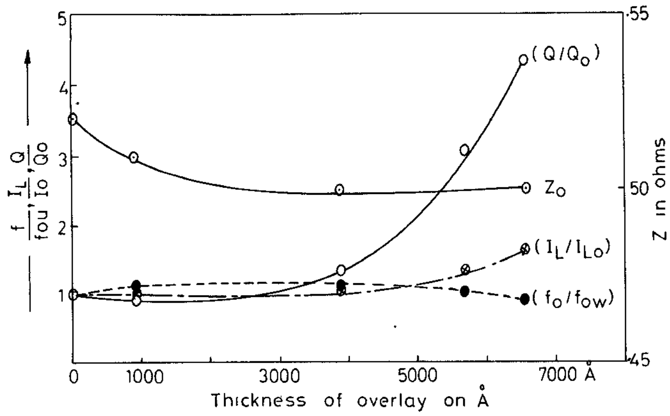

Fig. 2. Variation of Z_0, normalized values of Q, midband insertion loss I_L, and center frequency f_0 with thickness of Bi_2O_3 overlay.

6600 Å is low. It also shows that the line impedance has decreased only by about 4.2 percent (from 52.2 to 50 Ω) with increase in overlay thickness, over this thickness range. This result, obtained from TDR, is to be considered only as semiquantitative. However, it is in accordance with the general predictions about the impedance of a three-layer microstrip given by Farrar and Adams [16]. The measurements of insertion loss on the single microstrip over the whole frequency range with and without the Bi_2O_3 overlay indicate a loss of about 0.3 dB. The increase of Q, and also the small variation of insertion loss with Bi_2O_3 overlay, indicates that at X band Bi_2O_3 is not very lossy. The resistivities of the overlay films were of the order of 10^{12} Ω/sq or higher when measured with a vibrating condenser electrometer. The presence of Bi_2O_3 did not introduce any significant dispersive effect, as is shown by the constancy of f_0 and decrease in bandwidth.

Our measurements based on data for thickness less than 7000 Å of Bi_2O_3 overlay, on the Q of a half-wave open-circuited resonator (a rejection filter) indicate that there was an increase of approximately 4.5 times from the uncoated circuit to an identical circuit with an overlay of 6600 Å of Bi_2O_3. The Q improved in almost a weighted exponential manner. It can be assumed that this improvement in Q was caused by a lower radiation loss in the resonator with overlay. The field originally in air got concentrated more towards the substrate and considerably more energy propagated in the microstrip.

Now, the observed increase in Q_{total} indicates either a change in coupling or fewer losses—conductor, dielectric, or radiation. With the second of the possibilities, we may assume that the conductor loss has remained the same, as thickness and quality of metallization were kept constant and change in f_0 was not much.

The dielectric losses are inversely proportional to Q_d. Hence for an approximate qualitative assessment using [3, eq. (4)]

$$P_d \propto \tan\delta \cdot \frac{q\varepsilon_r}{\varepsilon_{\text{eff}}}$$

where

$$q = \frac{\varepsilon_{\text{eff}} - 1}{\varepsilon_r - 1}$$

therefore

$$P_d \propto \tan\delta \cdot \left(1 - \frac{1}{\varepsilon_{\text{eff}}}\right)\left(\frac{\varepsilon_r}{\varepsilon_r - 1}\right).$$

This indicates that the increase in ε_{eff} may increase P_d and decrease Q_{total}. We expect ε_{eff} to increase with Bi_2O_3 overlay. Further, our results on the straight line do not indicate much loss with the overlay, indicating constancy of $\tan\delta$.

It is felt, therefore, that increase in Q_{total} is caused by less radiated power, which is expected with increase in ε_{eff} from [3, eq. (10)]

$$P_r \propto \frac{480\pi(h/\lambda)^2 F(\varepsilon_{\text{eff}})}{Z_0}$$

as the function $F(\varepsilon_{\text{eff}})$ falls with increase in ε_{eff}. Note that Z_0 and f_0 have hardly changed.

If we consider the other possibility that there was a change in coupling, the increase in Q will need decrease in coupling. At the time of reporting of this short paper, our measurements on $\lambda/4$ section directional couplers had indicated a slight decrease in coupling and reasonable increase in isolation. (These results of subsequent experiments are being reported in a separate paper.) However, the decrease in coupling was not found to exceed 1 dB for the overlay range under consideration. This would change the Q by about 1.1 times at the maximum, as against the observed increase of 4.5 times.

From the data of Vendelin [17] it can be inferred that no surface wave or transverse mode coupling would occur in the frequency range with the thickness of substrate and linewidths used unless the ε_r changed by about nine times, which is excluded by our results.

The nominal values of the experimental parameters are $Q_0 = 45$, $f_{0w} = 9.586$ GHz, $I_{L0} = 5.6$ dB. The low values of Q_0 and I_{L0} are due to the unfortunate use of only two skin depths (1.2 μm) of gold layer. This was done to maintain sufficient adhesion of gold layer, required in further processing steps. The estimated conductor loss correction from our measured data indicates that the I_L would be about 14 dB and $Q_0 = 110$ for a 3-μm gold layer. Incidentally, the same circuit on a 3-μm copper layer gave Q of 200 and I_{L0} of 14.6 dB.

In conclusion, we can say that a thin-film overlay of high-dielectric-constant material can increase Q. This is possibly due to reduction in radiation loss. This, therefore, may also reduce the radiative cross coupling in the closely packed MIC's. If the overlay thickness is increased, we may expect that some surface-wave phenomena and dispersive effects may become more predominant. Further investigations are being made in our laboratory on coupled structures used for MIC work.

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Shuttle Pulse Measurement of Mode Coupling and Conversion

P. BERNARDI, F. BERTOLANI, AND F. VALDONI, MEMBER, IEEE

Abstract—**The measurement of weak coupling between two guided modes, for which the usual TE_{10} setups cannot be directly used, is dealt with. This problem mainly arises in coupling between different waveguides and in overmoded waveguides. In both cases a representation by means of two coupled lines is chosen, described by a directional coupler scattering matrix.**

In addition to the well-known resonant Klinger method, a new one, in the time domain, is suggested. This new method makes use of a shuttle pulse test set and starts from the observation of the envelope of an output signal, which under suitable conditions shows zeros related to the coupling to be measured.

Experimental results, with frequencies up to 90 GHz and couplings as low as −40 dB, confirm the accuracy and the sensitivity of the new method.

I. INTRODUCTION

This short paper deals with the measurement of weak coupling between two guided modes, in reciprocal lossy junctions for which the classical insertion-loss method cannot be easily applied. This very often occurs in directional couplers between different waveguides and in overmoded circular waveguides. Assuming for the latter case that the coupling between wanted and spurious modes, due to unavoidable imperfections or to the design itself (in tapers, elbows, mode launchers, etc.), can be separately taken into account for each spurious mode, and neglecting backward waves, the junction can be represented by a four-port scattering matrix as

$$S = \begin{vmatrix} 0 & S' \\ \tilde{S}' & 0 \end{vmatrix}. \qquad (1)$$

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P. Bernardi is with CSELT, Torino, Italy.
F. Bertolani is with the Fondazione Ugo Bordoni, Villa Griffone, Italy.
F. Valdoni is with the Istituto di Elettronica, University of Bologna, Villa Griffone, Italy.

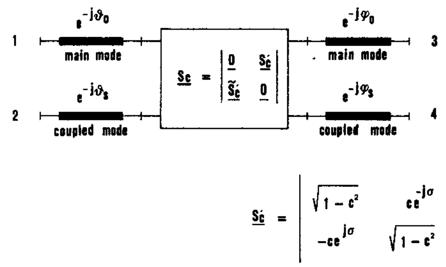

Fig. 1. Equivalent circuit of a coupled-mode junction.

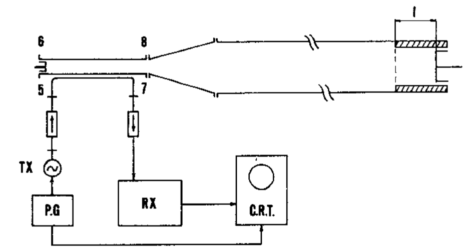

Fig. 2. Shuttle pulse setup used for conversion measurement.

Moreover, assuming a lossless coupling, S' becomes

$$S' = \begin{vmatrix} \sqrt{1-c^2}\, e^{-j(\theta_0+\phi_0)} & c e^{-j(\theta_0+\phi_s+\sigma)} \\ -\, c e^{-j(\theta_s+\phi_0-\sigma)} & \sqrt{1-c^2}\, e^{-j(\theta_s+\phi_s)} \end{vmatrix} \qquad (2)$$

where c and σ are the modulus and argument of the coupling, and θ, ϕ are complex parameters related to the main or wanted mode (subscript 0) and to the coupled or spurious one (subscript s). Under the preceding assumptions the junction can be represented as in Fig. 1.

When ports 2, 3, and 4 are short circuited, the reflection coefficient at port 1 becomes

$$\rho_1 = e^{-j2(\theta_0+\phi_0)} \frac{e^{-j2(\theta_s+\phi_s)} - T_2}{1 - T_1 e^{-j2(\theta_s+\phi_s)}} \qquad (3)$$

where

$$T_1 = 1 - c^2 + c^2 e^{-j2(\Delta\phi-\sigma)} \qquad (4)$$

$$T_2 = 1 - c^2 + c^2 e^{j2(\Delta\phi-\sigma)} \qquad (5)$$

and

$$\Delta\phi = \phi_0 - \phi_s. \qquad (6)$$

The evaluation of c can be performed by means of resonant methods [1]–[5] starting from measurements of ρ_1 [see (3)]. In some cases, as at millimeter wavelengths, a time-domain method, making use of a shuttle pulse test set, may be more convenient.

II. THE SHUTTLE PULSE METHOD FOR COUPLING MEASUREMENT

Let us consider the bilinear transformation of ρ_1 accomplished by means of the directional coupler of the shuttle pulse test set shown in Fig. 2. The transmission coefficient G, between the ports 5 and 7, can be expressed as

$$G = H - \frac{K}{1 + \rho_1 e^{-j2\psi}} \qquad (7)$$