FREQUENCY CHARACTERISTICS OF ELECTROMAGNETICALLY COUPLED (EMC) CIRCULAR MICROSTRIP PATCH (CMP) WITH ANGULAR VARIATION OF STRIP OVERLAY

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Abstract

The effect of angular variation of dielectric partial overlay on resonance frequencies of Circular Microstrip Patch (CMP) is studied by reflection measurements using Electromagnetic Coupling. The overlay of alumina strips with large range of, the widths and the thicknesses, are studied, as variable nondestructive perturbation of the CMP, with an aim to use it as a variable-parameter antenna. The change in resonance frequency is found to be much more non-linear than for the ring resonator (MRR). The best-fit equation for the resonance frequency is reported for the first time, for practically full perturbation range. The even mode is sensitive to these variations whereas odd mode is not (unlike MRR). A preliminary reflection/radiation study of CMP Antenna (CMPA) is indicated. Comparison is made with other reported microstrip structures.

Indexing terms: Circular Microstrip Patch, Electromagnetic Coupling, flexible perturbation, angle dependence, variable parameter antenna

I. INTRODUCTION

The two extensively reported configurations of microstrip resonators are linear transmission lines [1-5] and microstrip ring resonators (MRR) [6-13] (even nondestructively [10-13]). Reports are available of fixed-position perturbation on microstrip ring resonator [6-13], with different types of perturbations viz., notch [6], filled hole [7], gaps [8, 9] and nondestructive overlay of dielectric strip on the ring [10-13]. The last method has the advantage of flexibility of changing the perturbation (p) by variation of azimuthal angle (f) of overlay and also its strength by varying width [10, 11] and thickness [11] of the overlay. Hence the tailoring of resonator parameters is possible. Abegaonkar et al. [12, 13] have studied the perturbation of microstrip ring for grain moisture as a sensor application. There are reports of empirical equations for frequency variations [10-12], which are linear in (1+cos2f), with coefficients which are also linear in p. Abegaonkar et al. [13] have reported the non-linear variation of p for grain moisture sensor. Such microstrip patch resonators are extensively used as small-size antenna [14-17], including the Circular Microstrip Patch (CMP) mostly without overlays, except for one report [18] with full overlay on rectangular resonant antenna.

This article reports the effect of angle dependent perturbation of CMP as a resonator, by keeping partial overlay [10, 11] of alumina strips, with width (w) and thickness (t) variations, using flexibility of changing the angular position (f) of perturbation as well. This study aims at verifying whether the CMP has similar perturbation characteristics, as for ring resonator [10-13]. An attempt is made to give a very general empirical equation for frequency
variation effect for CMP. A preliminary reflection/radiation study of CMP Antenna (CMPA) is indicated.

II. EXPERIMENTS

The previous ring resonator studies are carried out [10-13] using transmission measurements with feed lines on the same substrate except [7]. In the present work, reflection measurements [7] are taken (which are more suited for antenna) on Scalar Network Analyzer (HP8757C), with highly flexible electromagnetic coupling (EMC) as for microstrip ring antenna (MRA), rectangular microstrip patch antenna (RMPA) [16, 17]. The experimentation consists of two parts (i) Design and fabrication of CMP, and (ii) characterization of a CMP under different perturbation conditions.

The CMP is designed to work at 10GHz by using cavity model method [14]. The patch (diameter, d=5.53mm) and the feed line is realized [see Fig.1(a) and 1(b)] on the second similar but separate substrates (25.4mm×25.4mm×0.635mm, Alumina εr=9.8), using copper metallization [16, 17]. One substrate (Sf) has a feed line on the top and the ground plane at the bottom, and the other substrate (Sp) has only the patch on the top. A thin layer of vacuum grease is used for ease of sticking and sliding of Sp on Sf with sufficient sticking [16, 17]. Fix position of Sp on Sf is used in this experiment, with the feed point fixed at nearly perfect match point (VSWR ≅ 1), at inset distance (d) = 0.900 ± 0.005mm (offset=0) from patch center [see Fig.1(c)]. The flexibility of EMC is not utilized in this work. At this point, CMP shows resonating frequency of 9.28GHz with bandwidth of 26.67MHz, Return Loss of −32.52dB and the Q factor of the resonator patch is about 340 (far better than for ring).

In the measurement part, the CMP is perturbed by keeping positional (φ) crossed partial overlay [10, 11] of alumina strips (εr=9.8, length=22mm) with varying w (1.0, 1.3, 1.5, 1.8, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5mm) and t (0.635mm×1 to 5). The azimuthal angle φ is varied from 0° to 360° in the step of 22.5° in all four quadrants [see Fig. 1(c)]. For each azimuthal position (φ) of the overlay the resonance frequency (f_{rp,φ}), Return Loss, VSWR and 3dB bandwidth are measured (not reported fully here). The maximum width that is used to perturb the CMP is 4.5mm because patch diameter is 5.53mm and similarly at the higher width t ≥ λ_g/4, the angular position of the overlay is not meaningful, because it becomes full overlay.

III. RESULTS AND DISCUSSION

A. The perturbation -strength effect on f_r of CMP, at θ°(f_{rp,θ°})

Figure 2 shows observed resonance frequency variation of CMP resonator due to overlay strip at position φ=0°, f_{rp,0°} with variation of width and thickness of overlay (i.e. with perturbation strength, p). The width (w) is normalized with respect to diameter of CMP (2R=5.53mm) and the thickness (t) with respect to substrate height (h=0.635mm). The resonance frequencies decrease with increase in width and thickness of the overlay. The variation of the resonance frequency is not very linear as seen by the bold line fit (in Fig.2). It follows roughly a 2nd degree equation.

Figure 3 shows the variation in effective dielectric constant of the overlay dielectric at 0° (ε_{eff,p,θ°}(f)) as a function of the width of the Alumina strips with thickness as a parameter. The frequency dependent effective dielectric constant of the system is calculated using the expression [19]
\[ \varepsilon_{\text{reff}}(f) = \varepsilon \frac{\varepsilon_r - \varepsilon_{\text{reff}}}{1 + \left( \frac{h}{Z_0} \right)^{1.33} \left( 0.43 f_{ro}^2 - 0.009 f_{ro}^2 \right)} \]  

(1)

\[ \varepsilon_{\text{reff}} \] is the static effective dielectric constant of the microstrip line which is calculated by the expression [22]

\[ \varepsilon_{\text{reff}} = \varepsilon_r + \frac{1}{2} \left[ 1 + \frac{29.98}{Z_0} \left( \frac{2}{\varepsilon_r + 1} \right)^{1/2} \left( \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \right) \left( \ln \frac{\pi}{2} + \frac{1}{\varepsilon_r} \ln \frac{4}{\pi} \right)^2 \right] \]  

(2)

where \( \varepsilon_r \) is the relative dielectric constant of the substrate, \( h \) is the height of the substrate in mm, and \( Z_0 \) is the characteristic impedance.

Change in \( \varepsilon_{\text{reff}}p,0°(f) \) is non-linear and depends on the width and thicknesses of the overlay. The effective dielectric constants increase with increase in width and thickness of the overlay (Fig.3). Experiment indicates a shift in the resonant frequency on the lower side confirming an increase in the effective permittivity.

The basic CMP structure has \( \varepsilon_r = 9.8 \) for the substrate below and \( \varepsilon_r \approx 1 \) in air above, giving effective dielectric constant between these two limits (\( \approx 7 \)) [3, 20]. For full overlay with \( \varepsilon_r \) higher than air [18, 20, 23], the field distribution will naturally change and become more TEM-like [19] and effective dielectric constant will increase from 7 towards 9.8 (see Fig.3)[10, 11, 23]. Hence we conclude that the resonator frequency, even for partial overlay, will fall with increasing volume (thickness and/or width) of the overlay [10, 11].

B. Angle Dependence

Figure 4 gives positional-angle dependence of the experimentally observed values of the perturbed resonance frequency, \( f_{p\phi} = f_{p\phi,0°} \) (\( f_{ro} \) being unperturbation \( f \)) for different widths and thicknesses of the overlay strip (only a sample data at \( t/h = 1 \) and \( w = 1.5 \) mm is given in Fig.4). It is clear from the figure that variation in resonance frequencies of CMP is dependent on not only the strength of perturbation (i.e. \( w, t \)) but also on the overlay angle \( \phi \), as expected [10-13].

The general equations for even and odd-mode frequency variations due to the perturbation (p) reported for microstrip ring resonator [10, 11] are as follows:

\[ f_{\text{odd}} = f_{ro} + a(p)(1 + \cos 2\phi) \]  

(Odd mode)  

(4a)

\[ f_{\text{even}} = [f_{ro} - k(p)] - a(p)(1 + \cos 2\phi) \]  

(Even mode)  

(4b)

where \( \phi \) is azimuthal angle of strip-position w.r.t feed line, \( k(p) \) and \( a(p) \) are the perturbation dependent factors, both of which are reported to be linear functions of width [10,11] and thickness [11] of overlay.
An important difference between the present data (Fig.4, the data points) and the above equation is that, (i) the even mode is sensitive to these variations whereas odd mode is not and (ii) the perturbation factors are non-linear functions, because the data points in Fig.4 could not be fitted with Eqn.4 (b), with linear perturbation factors. Rather it was found that second order term, \((1+\cos2\phi)^2\), is also needed, with a more general form as follows:

\[ f_{ip} = [f_{ro} - k(p)] - a(p)[1 + \cos2\phi] - b(p)[1+c\os2\phi]^2 \]  

where \(k(p)\) is constant factor, \(a(p)\) is the first order perturbation coefficient and \(b(p)\) is the second order perturbation coefficient.

It should be noted that we have used (see Fig.2) practically full range of \(w/2R\) (up to 0.8) and \(t/h\) (up to 5) for CMP as was done by Julie et al. [11] but for microstrip ring resonator (MRR), with linear equation in \((1+\cos2\phi)\). Thus variations obtained for CMP and for MRR are different. The normal general procedure, to fit the equation to the experimental data, followed here, is the same as Julie et al. [11], but in our case, as the variation, with \((1+\cos2\phi)\), is not linear, the procedure becomes more complex, which is given below

(i) \(\phi\) - dependence: It is expected [10-12] that \((f_{ro}-f_{ip})\) will be a function of \((1+\cos2\phi)\) [Eq.4]. Our data gives a second order fit (full lines in Fig.5) for CMP with functional constants \(k(p)\), \(a(p)\) and \(b(p)\) giving equation of form of Eq.(5) above. As a first step, families of curves are plotted, for 10 different \(w/2R\) covering practically full range of \(w\) at a fixed \(t/h\). We have a set of five such families of curves, for \(t/h = 1\) to 5. Fig. 5 gives only one sample curve at \(t/h = 1\).

(ii) \(w\) – dependence: (Second step), The above curves in turn give 3 sets of curves for the functional constants \(k(p)\), \(a(p)\) and \(b(p)\) as function of \((w/2R)\), for each of five \(t/h\) values (Fig.6a,b,c). On curve fitting (full lines in Fig.6), these also give second order equations. For example, for Fig.6 (a), we have 5 equations of form

\[ k(p)_w = k_0(p) + k_1(p)(w/2R) + k_2(p)(w/2R)^2 \]  

(iii) \(t\) – dependence: (Third step); These functional constants \(k_n\), \(a_n\) and \(b_n\) \((n = 0, 1, 2)\) were plotted against \((t/h)\), which gives 9 curves (not given). These curves were not as smooth as Fig.5 and 6 \((R^2\) on average is 0.9). We assumed them all to be 2nd order equations, (as an approximation) which gives, on curve fitting, the equations of the form [say for \(a(p)\)].

\[ a'(p)_t = a'_0(p) + a'_1(p)(t/h) + a'_2(p)(t/h)^2 \]  

(iv) This gives us the final equation [similar to Eq.(5)], which is just the combination of all above equations from step (i) to (iii). This general equation for both variables \((w, t)\) is found to be as follows:

\[ f_{ip} = [f_{ro} - K(p)] - A(p)[1 + \cos2\phi] - B(p)[1+\cos2\phi]^2 \]  

where,

\[ K(p) = k_0(p) + k_1(p)(w/2R) + k_2(p)(w/2R)^2 \]  

\[ A(p) = a_0(p) + a_1(p)(w/2R) + a_2(p)(w/2R)^2 \]
\[ B(p) = b_0(p) + b_1(p)(w/2R) + b_2(p)(w/2R)^2 \]  

with

\[ k_0(p) = 0.05978 - 0.01737(t/h) + 0.0045(t/h)^2 \]  
\[ k_1(p) = -0.39799 + 0.10589(t/h) - 0.02242(t/h)^2 \]  
\[ k_2(p) = 0.63803 + 0.06925(t/h) + 0.00643(t/h)^2 \]  
\[ a_0(p) = -0.09902 + 0.18029(t/h) - 0.02773(t/h)^2 \]  
\[ a_1(p) = 1.0751 - 1.02937(t/h) + 0.14918(t/h)^2 \]  
\[ a_2(p) = -1.10539 + 0.85522(t/h) - 0.14808(t/h)^2 \]  
\[ b_0(p) = 0.01907 - 0.07443(t/h) + 0.01081(t/h)^2 \]  
\[ b_1(p) = -0.22288 + 0.59123(t/h) - 0.07221(t/h)^2 \]  
\[ b_2(p) = 0.29835 - 0.42992(t/h) + 0.06306(t/h)^2 \]

The curves are generated using this general equation [Eq.(8)], (the full lines in Fig.4) and fitted to the experimentally data (the symbols representing experimentally observed values). These show only slight deviations. Thus it is seen that [Eq.(8)] is in good agreement with the experimental results. It is important to note here that these fits are not just power series fit, but it incorporates some guideline [using factor \((1+\cos^2 \phi)\)] from perturbation theory \([10, 24]\). To the best of our knowledge such relation \(f_{00}\), over wide range of perturbations, is not reported for CMP. At higher perturbation, the experimentally observed variations can be seen to fit the equation with slightly large errors. The best fit equation reported for ring resonator \([11]\) for both modes is linear in \((1+\cos^2 \phi)\) and hence simpler. But CMP has advantage that there is only a single mode present and errors due to geometric variations in delineation of patch will be less important.

C. Comparison with Similar Reported Studies:

There are only a few reports available for comparison with flexible positional partial overlay, as in our case. The exception is the microstrip ring resonator (MRR) and that for with fixed in-plane coupling \([9-13]\). We have used flexible input coupling as well, due to EMC. Our system (with flexible overlay and coupling) becomes most general and useful for any microstrip resonator study. Of course we have studied it only for circular microstrip patch (CMP). We are reporting full range data (of \(t\) and \(w\) variation) for CMP and the corresponding most general equation for frequency variation for resonator, which is somewhat similar to the reported e.g. for MRR \([10-13]\). Note that we have already taken the above data as the reflection parameters of CMPA (using EMC). Our preliminary results show that one can get bandwidth (BW) range from 0.01% to 7.9% with VSWR<2 [and even up to \(~40\%\) but with VSWR \(~3.5\)]. For MRA and RMPA may BW reported (with EMC) is 4.80%, 4.98\% \([16, 17]\) with VSWR<2, respectively. Thus the strip overlay perturbation can be applied to improve the bandwidth of CMPA.

Extensive studies on radiation pattern for CMPA with strip overlay are also studied mainly for alumina (\(w = 2\ mm,\ length = 22\ mm.\ and thickness = 0.635\ mm\)) because this strip dimension is about half of CMPA dimension and sufficiently perturbation of antenna...
system. Figure 7 is presented the effect of strip overlay on the E and H-plane radiation patterns of our antenna system. It can be seen that the amplitude of the lobe pattern change with changes in overlay angle. The maximum radiation amplitude is at 90° (see Fig. 7).

A comparison table 1 indicates that CMP has advantages over MRR for adjusting VSWR, going to nearly 1 (because of EMC), BW is narrower (with wider variation BW), Q is much higher, and loss much lower. Presence of only one (even) mode, w.r.t MRR (with split even/odd modes) may also be an advantage in applications for both resonator (i.e. sensor application [12-13]) and radiator.

CONCLUSION

The effect of wide range of perturbation using partial overlay with alumina strip (width and thickness) on the variation of the resonance frequencies of Circular Microstrip Patch (CMP) are found to be non-linear. CMP (and CMPA) has some advantages over MRR. The empirical equations accounting for the non-linear changes are reported, which are different from those of ring resonators. The report can be useful when CMP is used as a resonator/radiator with the inherent flexibilities of partial overlay and EMC.

REFERENCES


Figure 1: (a) Flared out view of two layered CMP with separate EMC feed (without overlay) (b) Cross-section of EMC CMP with overlay of Al₂O₃ (c) Overlay orientation and overlay of Alumina strip on the CMP at azimuthal angle $\phi = 45^\circ$ or $225^\circ$
Figure 2: Variation of perturbed resonance frequency [perturbation $p(t, w)$ at $\phi = 0^\circ$, (i.e. $f_{rp,0^\circ}$)] with width ($w/2R$) of the overlay for representative thickness ($t/h$), symbols for experimental data points: ■: $t/h=1$, ○: $t/h=2$, ▲: $t/h=3$, ▼: $t/h=4$, ★: $t/h=5$

Figure 3: Variation of effective permittivity [perturbation $p(t, w)$ at $\phi = 0^\circ$, (i.e. $\varepsilon_{reffp,0^\circ}(f)$)] with width ($w/2R$) of the overlay for representative thickness ($t/h$): ■: $t/h=1$, ○: $t/h=2$, ▲: $t/h=3$, ▼: $t/h=4$, ★: $t/h=5$
Figure 4: A typical variations for observed angle dependence of $f_p$ (data points) [along with validation of Eq.(8)- full lines]:

(a) Thickness ($t/h=1$) of the overlay with different widths ($w$):
- ■: $w = 1.0\text{mm}$,
- ○: $w = 1.3\text{mm}$,
- ▲: $w = 1.5\text{mm}$,
- ▽: $w = 1.8\text{mm}$,
- ★: $w = 2.0\text{mm}$,
- ◇: $w = 2.5\text{mm}$,
- ▼: $w = 3.0\text{mm}$,
- △: $w = 3.5\text{mm}$,
- □: $w = 4.0\text{mm}$,
- ◆: $w = 4.5\text{mm}$

(b) Width ($w=1.5\text{mm}$) of the overlay with different thicknesses ($t/h$):
- ■: $t/h = 1$,
- ○: $t/h = 2$,
- ▲: $t/h = 3$,
- ▽: $t/h = 4$,
- ★: $t/h = 5$
Figure 5: The variation of \( f_{ro-frp} \) from experimental data for 10 widths of overlay (\( w = 1.0 \) to 4.5mm) for \( t/h = 1 \) [along with best-fit curves-full lines, Eq.5]:
- \( \blacksquare \): \( w = 1.0 \)mm,
- \( \bigcirc \): \( w = 1.3 \)mm,
- \( \blacktriangle \): \( w = 1.5 \)mm,
- \( \triangledown \): \( w = 1.8 \)mm,
- \( \ast \): \( w = 2.0 \)mm,
- \( \bigtriangledown \): \( w = 2.5 \)mm,
- \( \blacklozenge \): \( w = 3.0 \)mm,
- \( \blacklozenge \): \( w = 3.5 \)mm,
- \( \bigcirc \): \( w = 4.0 \)mm,
- \( \ast \): \( w = 4.5 \)mm

Figure 6: Variation of perturbation factors: (a) \( k(p) \) \( \phi \) (b) \( a(p) \) \( \phi \) (c) \( b(p) \) \( \phi \) with width \( (w/2R) \) of overlay for representative thickness \( (t/h) \):
- \( \blacksquare \): \( t/h = 1 \),
- \( \bullet \): \( t/h = 2 \),
- \( \blacktriangle \): \( t/h = 3 \),
- \( \blacktriangledown \): \( t/h = 4 \),
- \( \ast \): \( t/h = 5 \) (to be continued).
Figure 6 (Cont.): Variation of perturbation factors: (a) $k(p)_\theta$ (b) $a(p)_\phi$ (c) $b(p)_\gamma$ with width ($w/2R$) of overlay for representative thickness $(t/h)$: ■: $t/h=1$, ●: $t/h=2$, ▲: $t/h=3$, ▼: $t/h=4$, ★: $t/h=5$
Figure 7: Typical E-plane radiation patterns for various overlay angle position and H-plane radiation patterns at 0° overlay angle and without overlay.
Table 1 Comparison of the different parameters of microstrip ring resonator (MRR) and circular microstrip patch resonator (CMP) (Curve fitting even of all are nearly same $t = 1$ to 5 and $W/2R = 0$ to 0.8)

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>YOGI ET AL [10], JULIE ET AL [11], ABEAGOANKAR ET AL [12, 13]</th>
<th>PRESENT EXPERIMENTAL RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed frequency (GHz)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Substrate $\varepsilon_{r}$ used</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td>Variation of frequency due to overlay</td>
<td>12.8%</td>
<td>17.6% **</td>
</tr>
<tr>
<td>Feed system</td>
<td>Fixed (feed line direct in plane)</td>
<td>EMC Adjust for best match VSWR $\cong 1$</td>
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<tr>
<td>Measurement method and flexibility</td>
<td>Transmission method Overlay flexibility</td>
<td>Reflection method Overlay and feed flexibility</td>
</tr>
<tr>
<td>Bandwidth at $f_r$</td>
<td>88MHz</td>
<td>27MHz</td>
</tr>
<tr>
<td>Variation of bandwidth with $t^<em>$, $w^</em>$ and $\phi^*$</td>
<td>65% 124MHz to 350MHz</td>
<td>95% 27MHz to 500MHz</td>
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<tr>
<td>Mode</td>
<td>Split mode (even/odd modes)</td>
<td>Single mode sensitive (even mode)</td>
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<tr>
<td>Quality factor</td>
<td>115</td>
<td>340</td>
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<tr>
<td>Loss at feed point (-dB)</td>
<td>-17.87 (Insertion loss)</td>
<td>-32.52 (Return Loss)</td>
</tr>
<tr>
<td>Thickness ($t$) and/or width ($w$) Range studied</td>
<td>$[10] t = 1, w/2R = 0$ to 0.27 $[11] t = 1-5, w/2R = 0$ to 0.8 $[10,11]$ linear equation $[12,13]$ for grain moisture application</td>
<td>$t = 1$ to 5 $w/2R = 0$ to 0.8 non linear equation</td>
</tr>
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</table>

* Thickness of overlay ($t$), width of overlay ($w$) and overlay angle ($\phi$)

** In addition, we can get frequency variation of basic CMP of variation 10% of $f_r$ ($f_r = 9.15$GHz to 10.02GHz by EMC adjustment (not used in present work)

† For MRR, we selected the best values of the three[10-13], the best Quality factor for MRR is 130, but at lower resonance frequency 9.67GHz, designed for 10GHz.