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Effect of Capacitive loading on slot loaded Dual Band Microstrip antenna

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Abstract- A novel technique for obtaining a single-layer single-feed dual-band microstrip antenna loaded with narrow slots having capacitive loading has been studied which shows tuning and reconfigurability at the two frequencies 1.72 GHz and 2.885 GHz respectively. By embedding a pair of slots of proper lengths close to the radiating edges, the rectangular patch has been shown to realize dual-band broadside directions. More freedom for tuning the resonant frequencies, the frequency ratio, and the input impedance are available because of more design parameters such as slot length and width and its position from radiating edges. The range of the frequency ratio (FR) that can be obtained is between 1.6 to 2. By varying the capacitance value (0.1 pF to 1pF), a tuning of around 100-160 MHz is achieved at both the frequencies. New empirical formulas are designed by modifying the formulas for reactively loaded patch with slot loading. Broadband antennas provide higher bandwidth at the expense of their high thickness. Dual band microstrip antenna with capacitive loading can be an alternative to large bandwidth antennas, especially when a large bandwidth is required for encompassing several narrowband channels. A FR4 substrate is used as a dielectric substrate. Simulations are performed using IE3D™.

Index Terms- Capacitive loading, Dual band, Microstrip antenna, Slot loading

I. Introduction

Patch antennas are popular for their well-known attractive features, such as a low profile, light weight, and compatibility with monolithic microwave integrated circuits (MMICs) [1]. Their main disadvantage is an intrinsic limitation in bandwidth, which is due to the resonant nature of the patch structure. In applications in which the increased bandwidth is needed for operating at two separate sub-bands, a valid alternative to the broadening of total bandwidth is represented by dual-frequency patch antennas. Indeed, the optimal antenna for a specific application is one that ensures the matching of the bandwidth of the transmitted and/or the received signal. Dual-frequency antennas exhibit a dual-resonant behavior in a single radiating structure. The trend of Synthetic Aperture Radar antennas of the future generation is to cover at least two of the three bands with a dual-band antenna. This would reduce the weight and surface area.

In this paper we study the effect of capacitive loading on the resonant frequencies with respect to variable tuning & frequency reconfiguration. Section 2 explains about slot loading. Section 3 describes capacitive loading and its effect on resonant frequency. Based on the results obtained empirical formulas for calculating two resonant frequencies f100 and f300 are devised. Section 4 explains the current distribution for TM100 and TM300 mode. Section 5 provides the results and Section 6 conclusion.

II. Slot Loading

Slots can be represented as the lumped circuit inductor, placed in series with the transmission line model for the patch antenna as in fig1. As the slots are moved away from the center of the patch, in either direction, the resonant frequency rises symmetrically (independent of which direction the slots are moved). In fact, the resonant frequency tuning curve maps out the cosine current distribution that develops on the patch with respect to length, except as an inverted cosine, since the lowest frequency tuning is at the current maximum, and the highest frequency tunings are where the lowest levels of current are i.e near the edges of the patch.

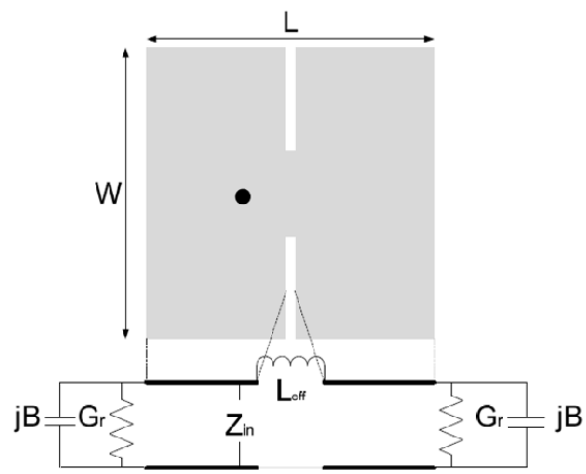

Fig1 Transmission line equivalent

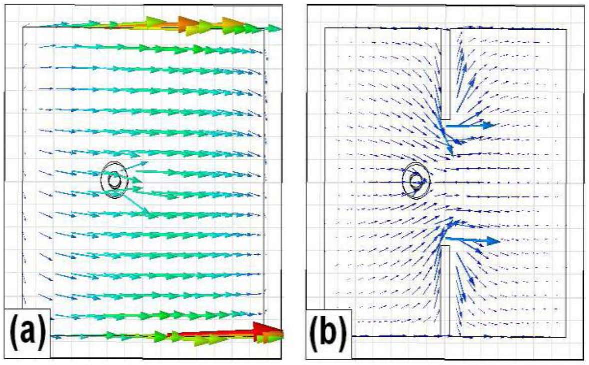

Fig. 2 Current distributions for TM100 mode (a) without slots & (b) with slots.

Figure 2 shows the current distribution on a patch surface with no slots, exciting the TM100 mode where the antenna is operating at resonant frequency of 1.72 GHz (in fig 2a). The patch without slots allows a straight path across the patch, whereas the slots force currents to take a longer path, as in Figure 2b. This longer path corresponds to a longer resonant length, thereby tuning the patch to 1.357GHz, a reduction in the resonant frequency of 363 MHz. Here the slots are placed at the midpoint of the patch, but they can be located anywhere along the patch if they change the current paths. One important consideration in placement of the slots is the polarization desired, as asymmetric slot placement can potentially cause cross-polarization levels to rise. For asymmetric slots, resonant current paths can develop off the main axes of the patch, such as along a diagonal axis, producing radiation components along both of the main axes instead of only one axis. Increased cross-polarization will result in poor axial ratio for circular polarization, and coupling between the two orthogonal feeds will increase.

A kind of reactive loading can be introduced by etching slots on the patch. The slot loading allows for a strong modification of the resonant mode of a rectangular patch, particularly when the slots are oriented to cut the current lines of the unperturbed mode [5].

The basic geometry is a slotted rectangular-patch antenna, in which two narrow slots, with dimensions Ls, and Ws, are etched on the patch close to and parallel to the radiating edges. The location of the slots with respect to the patch is defined by the quantities w and l which are very small with respect to the dimensions L and W of the patch. The antenna may be fed with either an aperture or a probe feed [1].

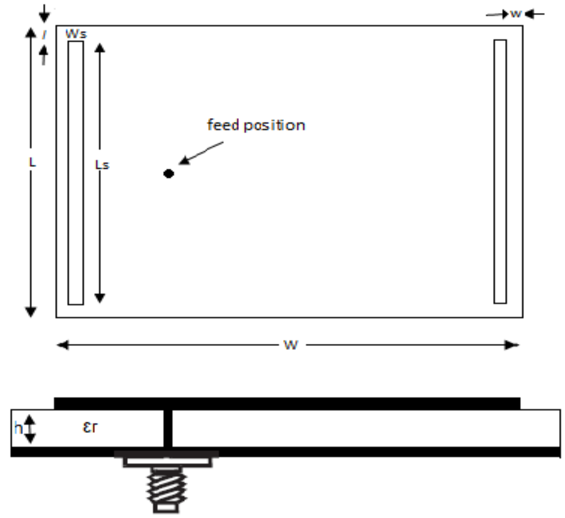

Fig 3 top & side view of designed antenna with parallel slots Authors have c probe feeding.

Further with slot loading, there is an increase in reactance at the radiating edges with slots etched parrallel to the radiating edge (see fig 1). It results in an increase in electrical length of the patch. Initially using the empirical formula for unslotted rectangular patch antenna [1] the width and length dimensions for an antenna operating at 1.72 GHz on FR4 substrate are
W= 53.25 mm & L= 41.5 mm.
For an antenna working at 1.72 GHz and 2.89 GHz, calculated patch dimensions [1] are
Type of feed- Coaxial feed at (-10, 0) from center.
W= 40 mm L=30 mm
h=1.575 mm
L/W= 0.75
Ls= 28 mm Ws= 1 mm
w= 1 mm l= 1 mm
Freq ratio= 1.68.

Table below gives the comparison for slotted and unslotted antenna with respect to their dimensions.

Sr no	Patch dimensions at 1.72 GHz	
	Unslotted patch	Slot loaded patch
1	W= 53.25 mm L= 41.5 mm	W= 40mm L= 30mm

Slot loading makes antenna look electrically larger in length, thus it helps in tuning a lower frequency on much reduced antenna size as compared to the unslotted antenna. thus the effective aperture of the antenna becomes lower due to reduction in antenna size which affects antenna directivity.
The TM100 mode that develops on the patch has a resonant frequency dependant on the length of the patch. While a high permittivity substrate will make the metal patch look electrically larger [10] by changing the wave propagation speed, another method used in tuning a microstrip antenna is loading the patch with slots. For a visual, intuitive explanation, the slots can be viewed as obstructions to the path of the current, forcing a longer physical distance for the current to travel.

When the two narrow slots are etched close to the radiating edges (small values of l and w); minor perturbations of TM100 are expected because the slots are located close to the current minima. The radiative mechanism associated with this first mode is essentially the same as that of a patch without slots. As a consequence, its resonant frequency is only slightly different from that of a standard patch. On the other hand, the slots are located where the current of the unperturbed TM300 should be significant, so that this current is strongly modified and it becomes similar to TM100. The two slots should not be too short or too displaced from the edges to avoid the deformation of the pattern associated with the upper frequency. These restrictions impose a limitation to the Frequency ratio (FR) that has to be lower than 2 and greater than 1.6.
The first resonance due to TM100 mode is not much affected by slot loading so that its frequencies can be obtained by slightly modifying the well established formula for rectangular unslotted patches [7]

$$f100 = \frac{c}{2(W + \Delta W' + \Delta W'')\sqrt{\varepsilon e\left(\frac{L}{h}, \varepsilon r\right)}} \qquad (1)$$

It is worth noting that the equivalent overlength ΔW" is that suggested in [1] for standard rectangular patches. The loading effect of the slot is effectively modelled by the term ΔW' that depends on l and w. The upper resonant frequency was predicted according to a simple transmission line model, which is derived by a direct inspection of the current distribution at the modified TM300 mode.The second frequency is predicted according to,

$$f300 = \frac{c}{2(L - 2l + Ls)\sqrt{\varepsilon e\left(\frac{w}{h}, \varepsilon r\right)}} \qquad (2)$$

The antenna is designed & simulated using IE3D™ electromagnetic simulation software which allows to solving for radio and microwave application. It works based on method of moment (MOM). The simulator tool computes most of the useful quantities of interest such as radiation pattern, input impedance and gain etc.
Fig 4 shows the graph for return loss v/s frequency obtained using IE3D™. With 10 dB as the reference for calculating Banwidth, the Bandwidth with center frequency as 1.721 GHz is 32 MHz and with center frequency as 2.885 GHz it was found to be 42 MHz. Fig 4 shows a plot showing a return loss of -16.9 dB and -35.9 dB at 1.72 GHz and 2.885 GHz respectively.

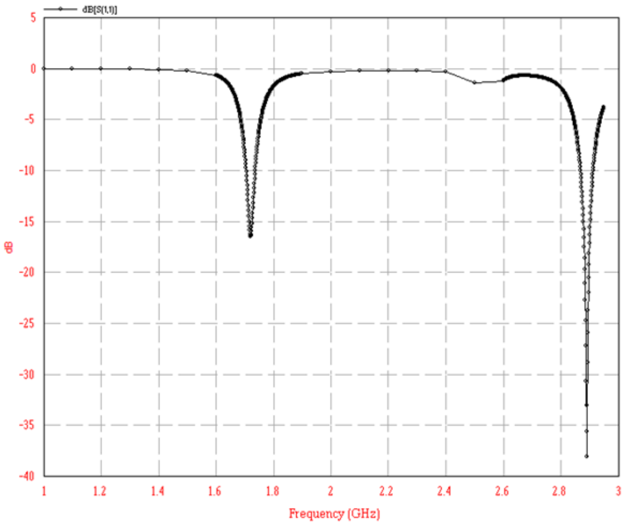

Fig 4 Return loss (dB) v/s frequency (Simulated)

Fig 5 shows a plot of return loss v/s frequency for the fabricated antenna. Results are obtained using Vector Network analayser. Fabricated antenna shows a resonance at 1.709 GHz and 2.86 GHz with a bandwidth of 50 MHz and 32 MHz at the respective frequencies.

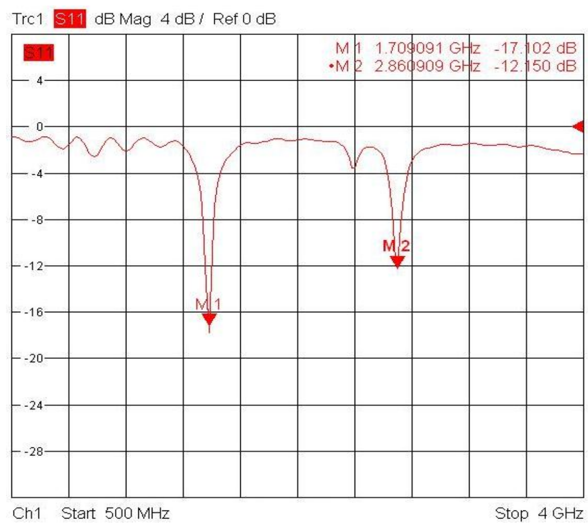

Fig 5 Return loss (dB) v/s frequency (Fabricated Antenna)

A Microstrip patch antenna radiates normal to its patch surface. The elevation pattern for Φ=0 and Φ=90 degrees would be important. Figure 6 & 7 show the 2D radiation pattern of the antenna at the designed frequency of 1.72 GHZ & 2.885GHz for Φ=0 and Φ=90 degrees in polar plot.

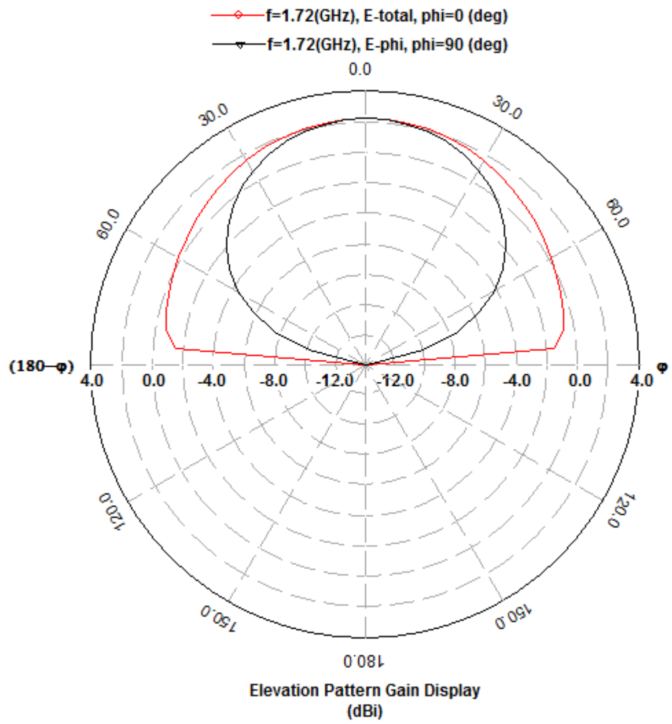

Fig 6 Elevation pattern gain display (dBi) at 1.72 GHz

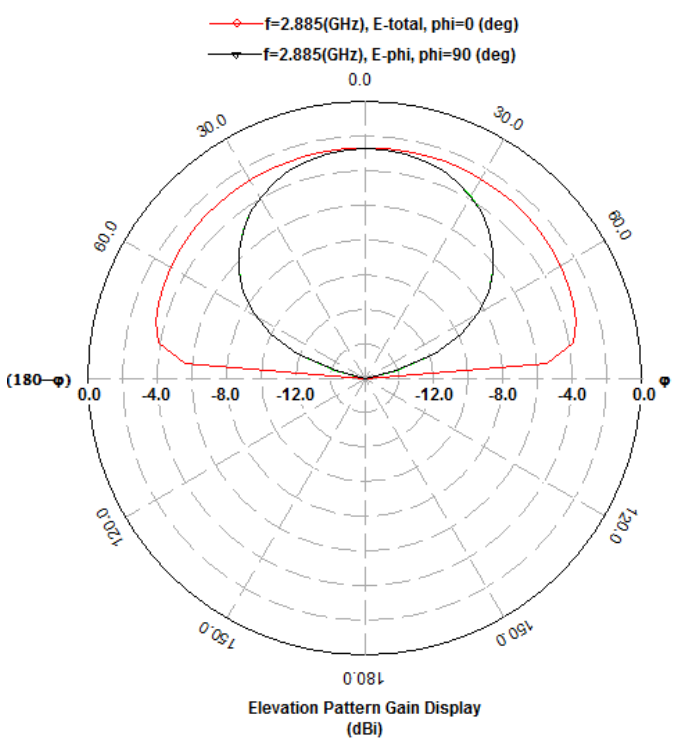

Fig 7 Elevation pattern gain display (dBi) at 2.885 GHz

Gain provided by the antenna is between 0-2 dBi. The low gains can be traced to the loss tangent of the FR4 substrate, which is 0.019.

III. CAPACITIVE LOADING

Slot loaded patch is subjected to capacitive loading by chip capacitor loading. The capacitance value can be also realised using varactor diodes with reverse bias voltage. Pair of chip-capacitors are attached across the slots centred on the y-axis to provide the required tuning. Capacitance value is varied from 0.1 pF to 1 pF and change in the two resonant frequencies is observed.

The configuration of the proposed single-feed dual-band rectangular microstrip antenna loaded with two narrow slots and two chip capacitors is depicted in Fig 8. The rectangular patch of size LxW is printed on a substrate of thickness h and relative permittivity εr. A pair of slots, length Ls and width Ws, are placed close to the radiating edges of the rectangular patch at a distance d. Pair of chip-capacitors are attached across the slots centred on the y-axis. Dual-frequency operation with the same polarisation planes and broadside radiation patterns can be obtained by using a single probe feed along the centreline between the two slots.

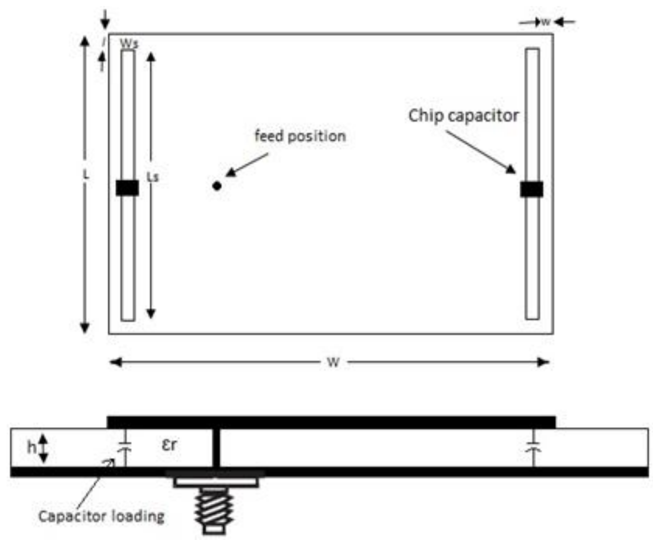

Fig 8- topview & sideview of designed antenna with parallel slots & capacitor loading

Frequency tuning can be obtained by varying the capacitance value. It is found that the resonance of the first (lower) operating mode (the perturbed TM100 mode) was slightly affected by the variation in the capacitance. However, the resonant frequency of the second (higher) operating mode (the perturbed TM300 mode) was decreased with increasing capacitance. However it's hard to obtain both frequency band and impedance matching with loaded capacitance larger than 1 pF (capacitance measured at 1 kHz) so frequency tuning is limited to capacitance value from 0.1 pF to 1 pF.

IV. CURRENT DISTRIBUTION

Simulated current distributions (for TM100 & TM300 mode) for the proposed design with capacitor loading are sketched in Fig. 9 using simulation software IE3D. With capacitor loading, the current has a similar distribution in TM100 mode and the frequency varies slightly from that of a patch without chip capacitors. However, loading capacitors strongly modify the current distribution in TM300 mode. The perturbed current around the slots is larger with loading capacitors and broadens the central venter of the current distribution.

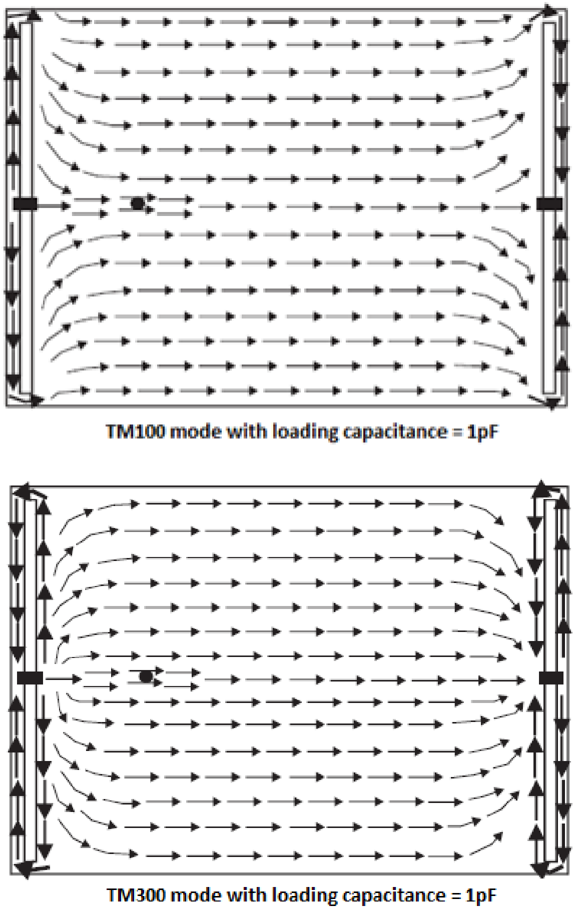

Fig 9 Simulated current distributions for slotted patch with capacitor loading

V. RESULTS

Fig 10 shows a plot of return loss v/s frequency for various capacitance values. Capacitance is varied from 0 to 1.0 pF to provide tuning and reconfigurability to the antenna. From the graph below it is observed that the capacitive loading provides a tuning over 100 MHz at first resonance and over 156 MHz at the second resonance. It's hard to obtain both frequency band and impedance matching with loaded capacitance larger than 1.0 pF (capacitance measured at 1 kHz) so frequency tuning is limited to capacitance value 1.0 pF.

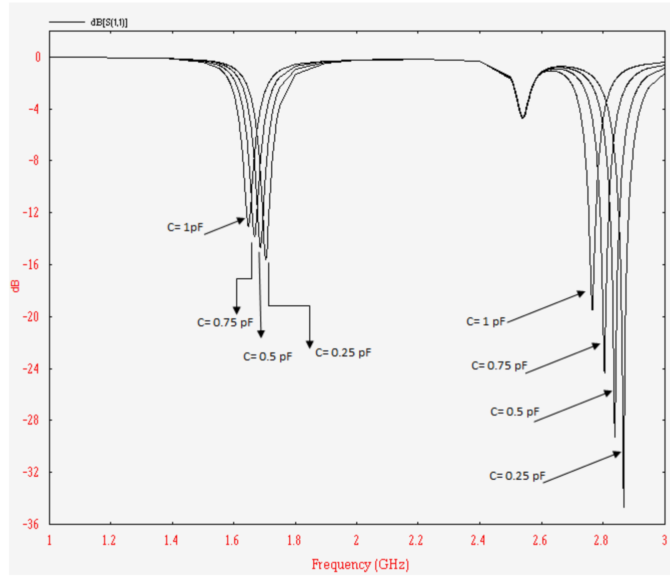

Fig 10 Return loss with varying capacitances

Figure 11 shows the measured input impedance on a Smith chart for C= 1.0 pF. Simulation results show good impedance matching at both the resonating frequencies for various capacitive loading (0 to 1.0 pF).

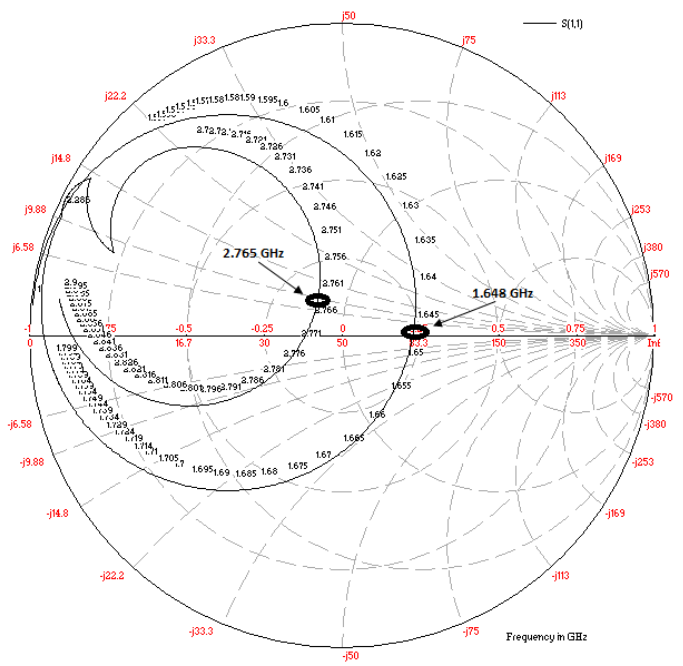

Fig 11 Measured input impedance on a Smith chart for proposed antenna with capacitive loading (C= 1pF)

By observing the results for different capacitive loads we can modify the equation (1) to calculate new resonant frequency (due to TM100 mode) with chip capacitor loading as

$$f100 = \frac{c}{2(W + \Delta W' + \Delta W'')\sqrt{\varepsilon e\left(\frac{L}{h}, \varepsilon r\right)} + x1Cap} \quad (3)$$

where Cap is the loaded capacitance value (between 0 to 1.0) defined in pF and x1= 7.7127.

c = free space velocity of light with length, width of the patch defined in mm. similarly the second resonant frequency with capacitive loading is obtained by curve fitting method. The approximate equation is obtained from equation (2) and is given as,

$$f300 = \frac{c}{2(L - 2l + Ls)\sqrt{\varepsilon e\left(\frac{W}{h}, \varepsilon r\right)} + x2Cap} \quad (4)$$

where Cap is loaded capacitance value (between 0 to 1) defined in pF and x2= 4.73. x1, x2 are the correction factor.

Similarly an approximate equation can be modelled by having capacitance as dependent variable and resonant frequency as independent variable as

Cap = -13.784*f100 + 23.729 (5)

Above equation is obtained by curve fitting method. Thus provides an alternative to user to set the antenna at preselected frequency and calculate the required capacitive load. The frequency ratio obtained is nearly same for all capacitive loads which is 1.681448. From this the second resonant frequency (f300) can be obtained which matches with the simulated results.

VI. Design Tools

The goal of this reactively loaded patch antenna is to have dual frequency response at preselected frequencies. The slotted patch is realised using IE3DTM Electromagnetic simulation software. Vector network analyser is used to calculate the parameters (Return loss, VSWR, Bandwidth etc) of the fabricated antenna.

VII. Conclusion

A new dual-frequency antenna has been studied that consists of a single layer patch with two narrow slots close to the radiating edges. The lower operating frequency is almost the same as that of a rectangular patch without slots; the upper frequency is well controlled by changing the slots length. Capacitive loading provides a tuning over 100 MHz at first resonance and over 156 MHz at second resonance thus can be an alternative to broadband antenna. New empirical formulas for calculating the resonance frequencies with capacitive loading are designed.

Gain provided by the antenna is between 0-1 dBi. The lower gains can be traced to the loss tangent of the FR4 substrate, which is 0.019. Higher gains are possible if lower-loss substrate materials are used, with gains of more than 4 dBi possible.

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Conclusion

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