Design and Parametric Analysis of a Dual Band Frequency Reconfigurable Planar Dipole Using a Dual Band Artificial Ground Plane

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ABSTRACT

This paper presents the design of dual band frequency reconfigurable fork shape planar dipole in the Industrial, Scientific and Medical (ISM) band (2.4GHz and 5.2 GHz). The proposed antenna can be used for WLAN applications. Antenna operates in dual as well as single band mode depending on switching combination. The proposed antenna gives bandwidth of 12.5% and 6.7% for 2.4 GHz and 5.2 GHz respectively in dual band mode while 15.5% for 2.4 GHz in single band mode. The performance of the antenna is analyzed with a ground-free substrate and traditional Perfect Electric Conductor (PEC) ground plane. The same antenna is mounted on a dual band slotted mushroom type Electromagnetic Bandgap (EBG) surface which improves the return loss of the antenna in both bands by -25 dB w. r. t. the PEC based dipole antenna. The proposed antenna can be used in WLAN applications. The simulations were carried out in SEMCAD and CST MWS.

Keywords:
Dual band, frequency reconfigurable, planar dipole, ISM band, single band, bandwidth, PEC, mushroom, EBG unit cell, EBG structure, CST MWS.

1. INTRODUCTION

Planar or micro-strip dipole antenna is widely used in Wireless Local Area Network (WLAN) communications [1]. The WLAN is standardized which put demand for antennas to provide inter-operability across the ISM frequency band. Planar dipole is metal conducting micro-strip, centrally interrupted with gap and feeding element, printed on one side of substrate [2, 3]. These dipoles can be used in a wide range of applications due to their advantages like conformability, light weight and low cost [1, 4]. In many applications a single antenna is required to transmit/receive electromagnetic waves at more than one resonant frequency. Planar or micro-strip dipole can be optimized to operate in multiple bands. Pin diodes [5], varactors [6, 7] and optical switches [8] can be used to design frequency reconfigurable planar dipoles. Although planar dipoles are low profile but they do not efficiently radiates in the vicinity of the PEC or metal ground plane. This is due to the fact that if the height of the radiating element (antenna) above the metal ground is less than one fourth of the wavelength, the image currents are out of phase with antenna currents, resulting in destructive interference. As a result the antenna return loss is dropped dramatically. The problem is addressed by using an artificial ground plane

(EBG) [9-11] to improve the radiation performance of the planar dipole.

EBG structures are artificial periodic or aperiodic meta-material structures that assist or prohibit the propagation of electromagnetic waves for specific bands of frequency for all incident angles and polarization [12].These structures exhibit the property of surface wave suppression and in-phase reflection for certain frequency bands of frequencies called ‘surface wave bandgap’ and ‘reflection phase bandwidth’ respectively. In this paper the in-phase reflection characteristics of the dual band EBG surface as a ground plane are used to design a low-profile frequency reconfigurable dipole.

In this article a frequency reconfigurable planar fork shaped dipole operating in WLAN bands is designed using optical switches and a multi-band EBG surface as a ground plane. The performance of the proposed antenna is compared with the planar dipole with a PEC ground plane at height of less than quarter of wavelength.

The rest of the paper is divided in the following sections; Section 2 presents the design methodology of the planar dipole and dual band EBG structure. The results are discussed in section 3. Section 4 concludes the paper.

2. Design Methodology

2.1 Design of the planar dipole on traditional substrate

The geometry of the fork shape planar dipole is shown in Fig. 1. The substrate material is 1.6 mm thick FR-4 with a relative permittivity of 4.4. The total length of the dipole, L (43 mm) gives resonance at the lower frequency (i.e. 2.4 GHz). W (3.33 mm) represents the total width of the dipole. The dipole consists of two forks type structure placed back to back. Each fork consists of two arms of same widths $w_1=w_2$ (1.11 mm). In reconfigurable antenna designs, switches are used to alter the radiation characteristics (frequency in this case). Two slots (s_1, s_2) of 1 mm length in the lower arms of dipole, are introduced to insert the switches for frequency reconfigurable operation. The shorter dipole arms of length L_3 (6.4 mm) results in resonance at higher frequency (5.2 GHz), depending on the status of the switch. Two forks of the dipole are separated with feed gap of G (1.5 mm). The antenna is fed SMA coaxial port.

The magnitudes of the above resonant lengths for the dual frequencies were determined by using the theory of the transmission line model [4]. The resonant lengths (L, L_3) for 2.4 GHz and 5.2 GHz bands are optimized in terms of guided wavelength $\lambda_{2.4GHz}$ and $\lambda_{5.2GHz}$ respectively which depend on the effective relative permittivity [4]:

$$L_1 = L_2 = \lambda_{2.4GHz}/4 \qquad (1)$$

$$L_3 = \lambda_{5.2GHz}/4 \qquad (2)$$

The guided wavelength at the resonant frequency is

$$\lambda_{f_r\,GHz} = \frac{c}{f_r\sqrt{\varepsilon_e}} \qquad (3)$$

c = Velocity of light (m/s)
f_r= Resonating frequency (2.4 or 5.2 GHz) and

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\sqrt{(1 + 12\,t\,/\,W)}\right]^{-1} \qquad (4)$$

ε_e = Effective permittivity
ε_r = Relative permittivity
t = Thickness of substrate (mm)
w= width of the dipole (mm)

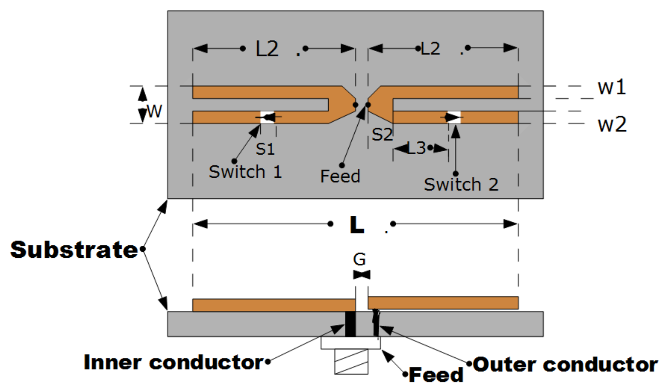

Fig. 1: Proposed dual band frequency reconfigurable dipole planar layout (top and side view) *(L = 43 mm, G = 1.5 mm, W = 3.33, w1=w2=1.11, mm L3 = 6.4 mm, s1=1mm, s2=4 mm).*

2.2 Design of planar dipole on artificial ground plane

To design a low-profile, dual band planar dipole, a mushroom type [9] EBG structure is used to achieve in-phase reflection [10, 11] in the desired frequency bands (i.e. 2.4 and 5.2 GHz). The dimensions of the square unit cell for dual band operation (Fig. 2) are obtained using the well-known Sievenpiper [9] mushroom type EBG equations. Resonant frequency of the EBG surface is given by:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (5)$$

Where, C is the surface capacitance due to fringing between the neighboring unit cells, given by:

$$C = \frac{w\varepsilon_0(1+\varepsilon_r)}{\pi}\cosh^{-1}\left(\frac{x+g}{g}\right) \qquad (6)$$

Where $x=a$ or $x=l_x$ is the width of patch for in-phase reflection at 2.4 and 5.2 GHz respectively. The surface inductance L is proportional to length of metal via (or thickness t of the substrate), i.e.

$$L = \mu t \quad (7)$$

Where, $\mu = \mu_0\mu_r$. A 1.6 mm thick FR-4 is used as substrate. Cylindrical metal via of radius 0.5 mm are used to connect the center of the patch to the bottom ground. The larger patch ($a = 0.21\lambda_{2.4\,GHz}$= 19 mm) gives in-phase reflection at 2.4 GHz as shown in Fig. 3. The gap between the neighboring EBG patches is $g = 0.02\lambda_{2.4\,GHz}$=1mm. The width of the smaller patch is opt l_x=11.95 mm which gives in-phase reflection at 5.2 GHz. The slot or separation between smaller patch and larger patch is b = 0.5 mm.

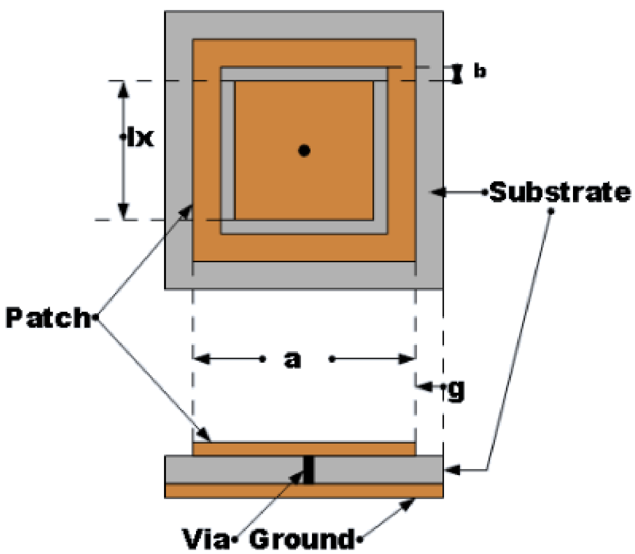

Fig. 2: Top and side view of unit cell of dual band EBG, a= 19 mm, g=1 mm, l_x=11.95 mm, b=0.5 mm

EBG unit cells are periodically arranged along x and y dimensions in order to form the ground plane of a given size. In this paper the performance of the antenna is studied at various heights from the dual-band EBG ground planes of different sizes {i.e. 5 x 5 EBG (100 x 100 mm), 9 x 9 EBG (160 x 160 mm) and 15 x 15 EBG (300 x 300 mm)}. Fig. 4 shows the top and side views for 5x5 EBG cell structure. The proposed antenna with long $\lambda/4$ 'bazooka' balun [4] is fed via a coaxial cable. The length of the balun is 31.25 mm. Lower part of bazooka balun is connected with outer conductor of coaxial cable while the upper part is left open in order to provide very high impedance [4].

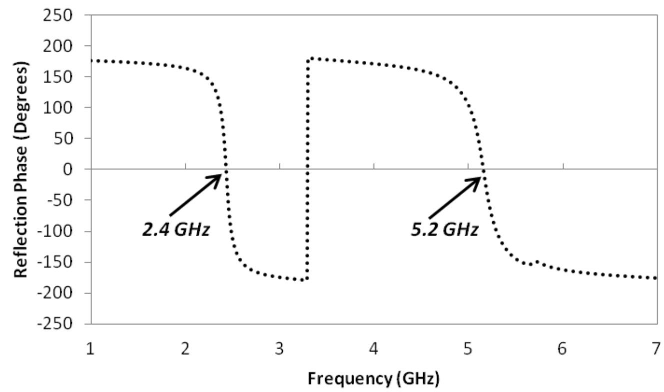

Fig. 3: Response for frequency bandgap of proposed EBG unit cell

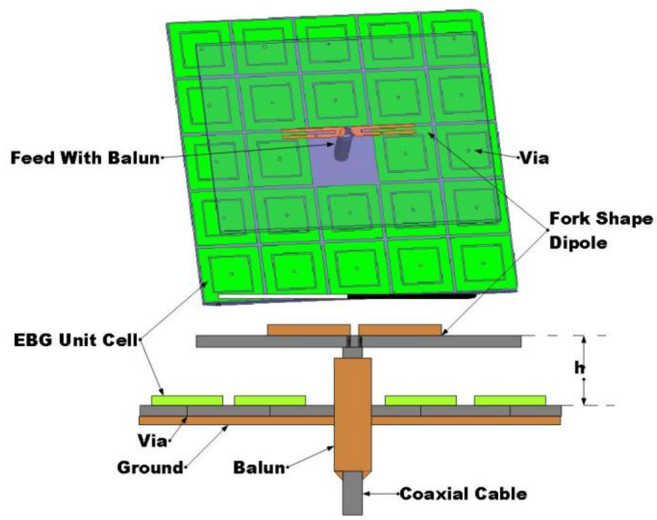

Fig. 4: Top and side view of planar dipole mounted at a height h from a 5x5 dual band EBG cell structure

3 RESULTSAnalysis of planar dipole on ground-free substrate (no conducting ground plane)

The switching modes outlined in Table 1 are used to reconfigure the frequency of the dipole (Fig. 1). When both switches are OFF dipole operates in dual band at 2.4 GHz and 5.2 GHz with a return loss of -22.6 dB and -20 dB respectively. The -10 dB return loss bandwidth at 2.4 and 5.2 GHz is 12.5% and 6.7% respectively.

TABLE 1: SWITCHING MODES FOR FREQUENCY RECONFIGURABLE OPERATION

S. No	Switch 1	Switch 2	Frequency Mode
1	ON	ON	Single band (2.4GHz)
2	OFF	OFF	Dual band (2.4 and 5.2GHz)

When both switches are ON dipole operates in single band (2.4 GHz) mode. The return loss and bandwidth in this mode is -24.5 dB and 15.5 % respectively (Figure 5).

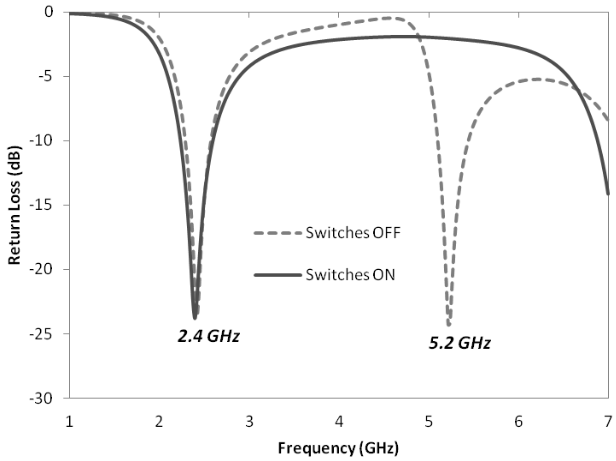

Fig. 5: Without EBG, when both switches are OFF and ON (L = 43 mm, G = 1.5 mm, W = 3.33, $w1$=$w2$=1.11, mm $L3$ = 6.4 mm, $s1$=1mm, $s2$=4 mm).

The *E* and *H*-plane gain patterns of the planar dipole for 2.4 and 5.2 GHz bands for a given status of the switches is portrayed in Fig. 6. When both switches are OFF antenna operates in dual band mode with an *E*-plane gain of 2.1 dB for 2.4 GHz band while 1.79 dB for 5.2 GHz band. The planar dipole operates in single band mode with a gain of 2.2 dB when the switches are closed. The *H*-plane gain remains unchanged for both bands irrespective of the status of the switches.

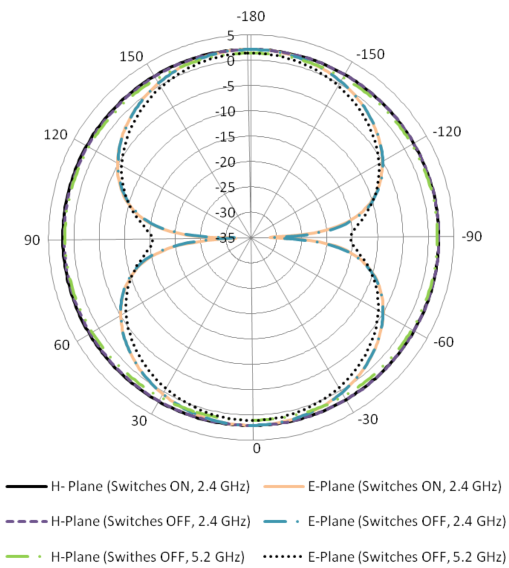

Fig. 6: Comparison of (E, H) –plane radiation pattern of dipole antenna (Fig. 1) at 2.4 and 5.2 GHz for ON and OFF switching modes

3.2 Analysis of planar dipole with PEC Ground Plane

The return loss of the antenna in the presence of PEC ground plane (Fig. 7) at a height less than $\lambda_{2.4GHz}/4$ (i.e. $h=0.104\lambda_{2.4GHz}$=13 mm) is depicted in Fig. 8. The height h=13 mm is taken for the purpose of comparison when the antenna is mounted on an EBG ground plane. The degradation in the return loss and -10 dB bandwidth at 2.4 and 5.2 GHz is due out of phase reflection of image currents.

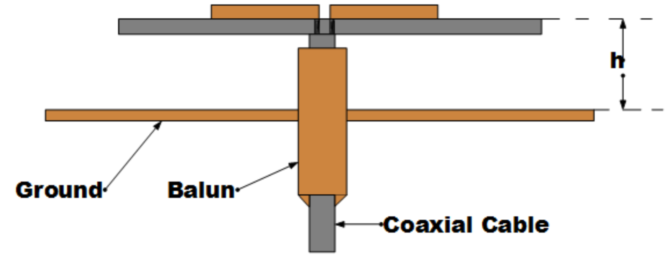

Fig. 7: Dipole antenna with a PEC ground plane at $h=0.104\lambda_{2.4GHz}$

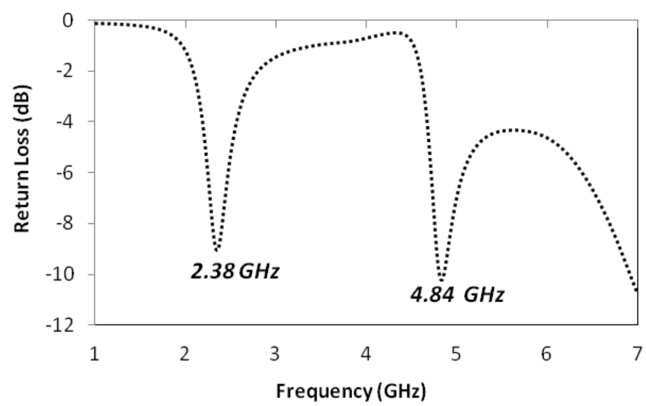

Fig. 8: Return loss of the dipole with a PEC ground plane at $h=0.104\lambda_{2.4GHz}$

3.3 Parametric analysis of planar dipole with 9x9 EBG plane at different heights

Dual band mode: The return loss for the antenna, mounted at different heights ($h=0.0625\lambda_{2.4GHz}$, $0.088\lambda_{2.4GHz}$, $0.104\lambda_{2.4GHz}$, $0.125\lambda_{2.4GHz}$) above a 9 x 9 EBG ground plane, in dual band mode is illustrated in Fig. 9.

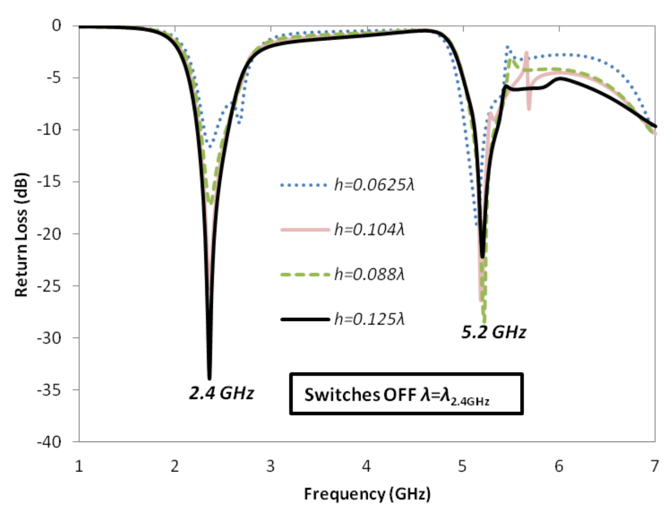

Fig. 9: Return loss comparison (switches=*OFF*) for planer dipole over a 9 x 9 EBG at h= $0.0625\lambda_{2.4GHz}$, $0.088\lambda_{2.4GHz}$, $0.104\lambda_{2.4GHz}$ and $0.125\lambda_{2.4GHz}$

If the radiating element (dipole) is placed at a height of $0.0625\lambda_{2.4GHz}$ above the ground, its return loss is badly affected. It is observed that as antenna height from EBG increases, its return loss is improved for the lower band (2.4GHz). It is worth noting that as the height decreases, a significant improvement in return loss and bandwidth at the higher band (5.2 GHz) is observed. These observations are summarized in Table 2.

TABLE 2: BANDWIDTH COMPARISON OF ANTENNA IN DUAL BAND MODE

S.NO	Height of antenna above EBG plane (*h*)	Bandwidth (%)	
		2.4 GHz	5.2 GHz
1.	$0.0625\lambda_{2.4GHz}$	5.83	4.03
2.	$0.088\lambda_{2.4GHz}$	10	4.23
3	$0.104\lambda_{2.4GHz}$	10	3.46
4	$0.125\lambda_{2.4GHz}$	14.16	4.615

Single band mode: When both the switches are *ON*, antenna fixed at different heights above the EBG ground plane operates in single band mode (2.4 GHz) as demonstrated in Fig. 10 and summarized in Table 3. From this analysis it is apparent h=$0.104\lambda_{2.4GHz}$ and $0.125\lambda_{2.4GHz}$ are optimum heights for antenna to be mounted on an EBG structure in order to give better return loss.

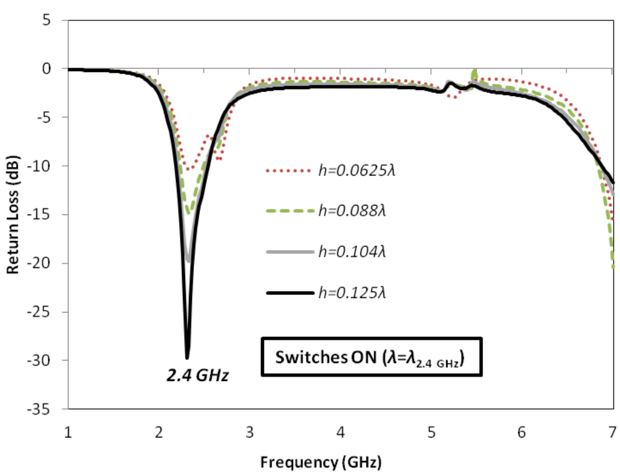

Fig. 10: Return loss comparison (switches=*ON*) for dipole over 9 x 9 EBG at h= $0.0625\lambda_{2.4GHz}$, $0.088\lambda_{2.4GHz}$, $0.104\lambda_{2.4GHz}$ and $0.125\lambda_{2.4GHz}$

TABLE 3: BANDWIDTH COMPARISON OF THE ANTENNA OPERATING IN SINGLE BAND MODE

S.NO	Height of the antenna above EBG plane (*h*)	Bandwidth (%) 2.4 GHz
1	$0.0625\lambda_{2.4GHz}$	<1
2	$0.088\lambda_{2.4GHz}$	7.5
3	$0.104\lambda_{2.4GHz}$	13.33
4	$0.125\lambda\lambda_{2.4GHz}$	15

3.4 Parametric analysis of the antenna by varying the size of the EBG ground plane for a fixed height (*h*)

The performance of proposed antenna is analyzed with EBG ground plane of various sizes, i.e., 100mm x 100mm (5x5 unit cells), 300mm x 300mm (15x15 unit cells) and PEC ground Plane. Fig. 11, 12 and Fig. 13, 14 shows the comparison in terms of return loss/bandwidth of planar dipole antenna at two different heights above ground planes of varying size in single and dual band modes respectively. The greater the size of the ground plane, the better is the performance of the antenna for a specified height over the ground. Summary of the results is presented in Table 4

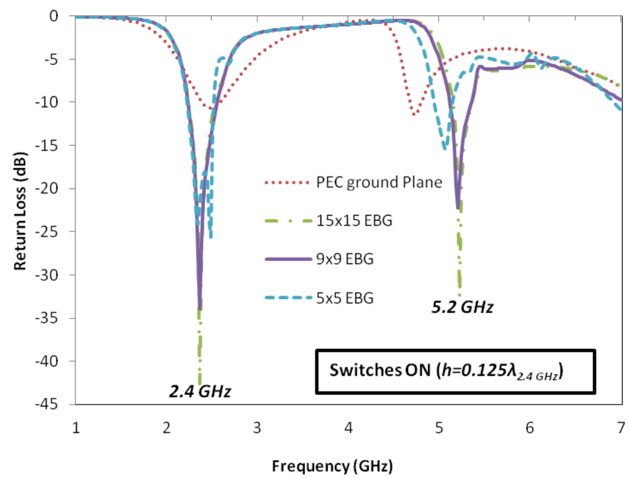

Fig. 11: Return loss of planar dipole in dual band mode at h= $0.125\lambda_{2.4GHz}$

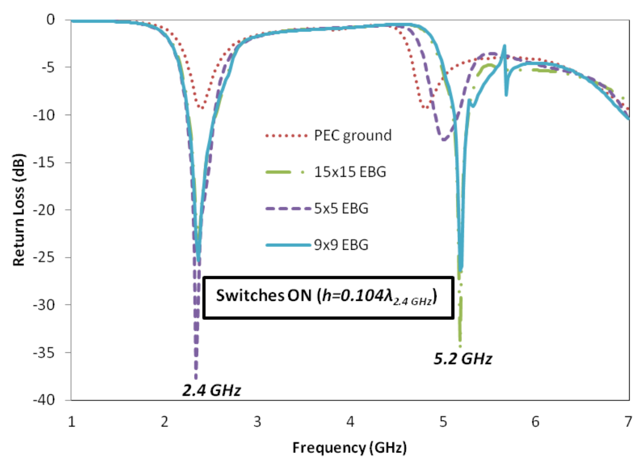

Fig. 12: Return loss of planar dipole in dual band mode at h= $0.104\lambda_{2.4GHz}$

TABLE 4: BANDWIDTH COMPARISON OF THE ANTENNA ON EBG STRUCTURES OF VARYING SIZES FOR FIXED HEIGHTS

S.NO	Ground Plane	BW (%) at h= $0.125\lambda_{2.4GHz}$		BW (%) at h=$0.104\lambda_{2.4GHz}$	
		2.4GHz	5.2GHz	2.4 GHz	5.2GHz
1	PEC	<1	<1	<1	<1
2	5x5 EBG	12.5	<1	12.5	<1
3	9x9 EBG	14.16	4.615	10	3.46
4	15x15 EBG	12.5	4.23	10.8	4.2

For demonstration purpose the snap shots of electric field strengths of the planar dipole mounted on an EBG ground plane for single and dual band modes are illustrated in Fig.

15 and 16 respectively. When both switches are ON the four arms of the fork shape planar dipole radiates at 2.4 GHz (Fig. 15). On the other hand when both switches are OFF, the upper arms of the dipole radiates at 2.4 GHz whereas the lower arms radiates at 5.2 GHz (Fig. 16). The *E*-field strength along the length of the dipole antenna is maximum at the right-most and left-most edges for a given frequency mode.

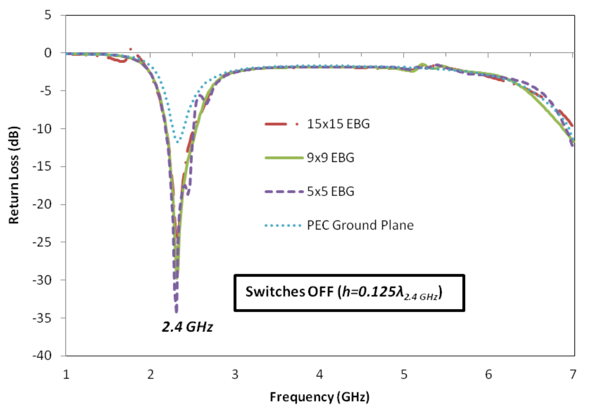

Fig. 13: Return loss of planar dipole in single band mode at $h = 0.125\lambda_{2.4GHz}$

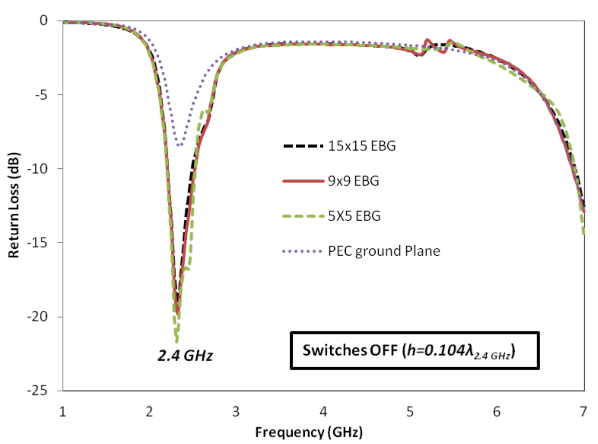

Fig. 14: Return loss of planar dipole in single band mode at $h = 0.104\lambda_{2.4GHz}$

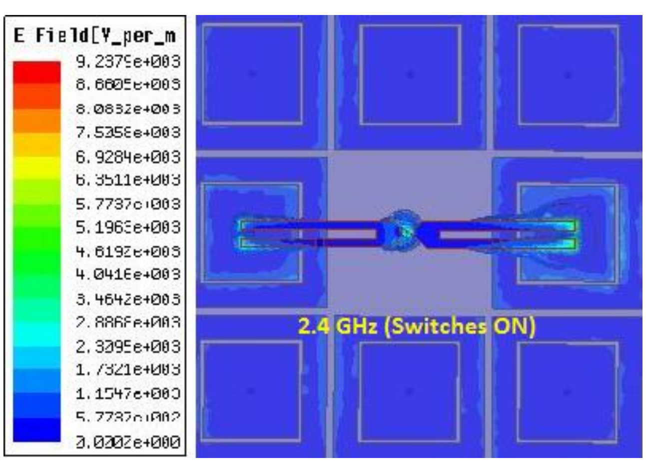

Fig. 15: *E*-field strength (Vm^{-1}) of dipole on EBG in single band mode

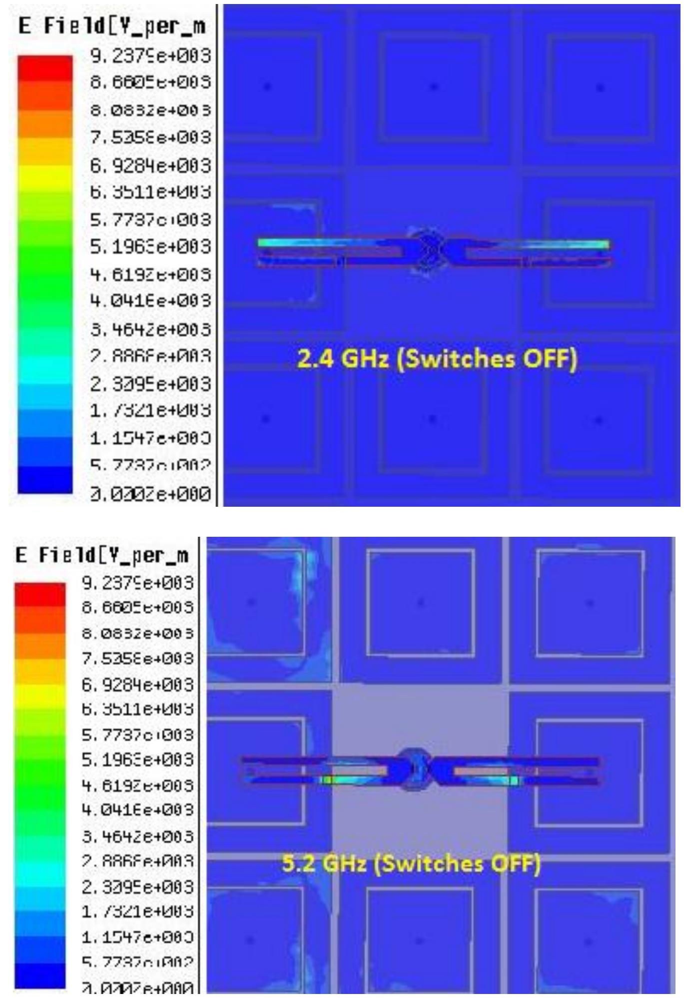

Fig. 16: *E*-field strength (Vm^{-1}) of dipole on EBG in dual band mode

4. CONCLUSION

A dual band frequency reconfigurable fork shape planar dipole for 2.4 GHz and 5.2 GHz ISM band has been proposed. Frequency re-configurability has been achieved by using optical switches. Proposed antenna operates for single band of 2.4 GHz in *ON* switching mode and in dual band of 2.4GHz and 5.2 GHz in *OFF* switching mode. The said antenna was implemented on dual band mushroom type EBG structure at different heights from antenna. The antenna return loss characteristics were analyzed at height of less than quarter of a wavelength (i.e. $h = 0.104\lambda_{2.4GHz}$ and $0.125\lambda_{2.4GHz}$) above an EBG structure of different sizes and compared with the antenna on PEC ground plane. Bazooka balun was used to match input impedance of antenna with coaxial feed. It is found that -10 dB return loss bandwidth of the PEC based reconfigurable antenna is reduced by more than 14 % if compared with the proposed antenna on an EBG ground plane. The antenna can be used in low profile WLAN applications.

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