Gap-Coupling: A Potential Method for Enhancing the Bandwidth of Microstrip Antennas

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ABSTRACT

In this paper, a technical review on gap-coupled microstrip antennas is presented. The gap-coupled microstrip antennas give a large bandwidth as compared to the conventional microstrip antennas. The method of bandwidth enhancement using gap-coupled microstrip antennas has been elaborated. The gap-coupled microstrip antennas also produce two resonances. The dual frequency operation of the gap-coupled microstrip antenna is also described. A research overview of gap-coupled microstrip antennas, challenges, types of gap-coupled microstrip antennas as well as numerical methods of calculating various parameters of the gap-coupled microstrip antennas are discussed in this paper.

Keywords: Gap-coupling; Dual frequency; Bandwidth enhancement; Quality factor.

1. Introduction

Microstrip antennas are preferred in various applications due to several advantages of these antennas as compared to the conventional antennas. Some of the principal advantages of microstrip antennas are light weight, low volume, thin profile configuration, low fabrication cost, conformability to mounting hosts, isotropic radiation characteristics, negligible human body effect, no cavity backing is required, feed lines and matching network can be fabricated easily on the same substrate [1]. However, microstrip antennas have also some limitations as compared to conventional antennas. The major limitations of these antennas are narrow impedance bandwidth, low gain, large ohmic loss in the feed structure of arrays, most microstrip antennas radiate into half-space, complex feed structures required for high performance, spurious radiation from feeds and junctions, and the size of microstrip antennas becomes larger at lower frequencies. Microstrip antennas fabricated on a substrate with a high dielectric constant are strongly preferred for easy integration with MMIC RF front-end circuitry, however, use of high dielectric constant leads to poor efficiency and narrow bandwidth [1–4].

Narrow bandwidth is a major disadvantage of microstrip antennas in practical applications. Many bandwidth-enhancement or broadband techniques for microstrip antennas have been reported. One potential technique for bandwidth enhancement uses coplanar directly coupled and gap-coupled parasitic patches [5]. Decreasing the quality factor of a microstrip antenna is also an effective way of increasing the antenna's impedance bandwidth. This kind of bandwidth-enhancement technique includes the use of a thick air or foam substrate [6, 7] and the loading of a chip resistor on a microstrip antenna with a thin dielectric substrate [8, 9]. The bandwidth of microstrip antennas is inversely proportional to their quality factor. The quality factor of a resonator is defined as the ratio of energy stored to the power radiated. By changing the substrate parameters such as dielectric constant and thickness, the quality factor can be varied. By decreasing the dielectric constant, the bandwidth of the microstrip antennas can be increased [10], due to the decrease in the dielectric constant, the stored energy decreases and the radiated power increases, so the quality factor decreases, and hence the bandwidth increases. Similarly, on increasing the thickness of the substrate the stored energy decreases, hence the quality factor decreases and the bandwidth of the antenna increases [10]. But there are many disadvantages of increasing the thickness of the substrate and of using lower dielectric constants, such as increasing surface wave power resulting poor radiation efficiency.

In this paper, a survey to the gap-coupled microstrip antennas is presented. The concept of enhancing the bandwidth and the concept of dual frequency operation using gap-coupling have been elaborated. The numerical modelling, applications, and challenges are also described. Rest of the paper is organized

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as follows. Section 2 gives the concept of bandwidth enhancement and dual frequency operations using gap-coupling. The research overview of the gap-coupled microstrip antennas is given in section 3. The numerical modelling of the gap-coupled microstrip antennas is described in section 4. Section 5 gives various applications and challenges of gap-coupled microstrip antennas. Finally, section 6 concludes the work.

2. Bandwidth enhancement and dual frequency operation using gap-coupled microstrip antennas

The bandwidth of the microstrip antennas can be improved by using the gap-coupled structure. In this structure, a parasitic patch is placed close to the feed patch as shown in Fig. 1, and gets excited through the coupling between the patches. The feed patch is excited by a feeding method and the parasitic patch is excited by gap-coupling. If the resonant frequencies f_1 and f_2 of these two patches are close to each other, then broad bandwidth is obtained as shown in Fig. 2. The overall input return loss will be the superposition of the responses of the two resonators resulting in a wide bandwidth [11]. By adjusting the feed location and various dimension parameters of the gap-coupled microstrip antennas, the bandwidth can be enhanced. If the dimensions of the feed patch and parasitic patch are same, due to coupling the coupled structure creates two different resonant frequencies.

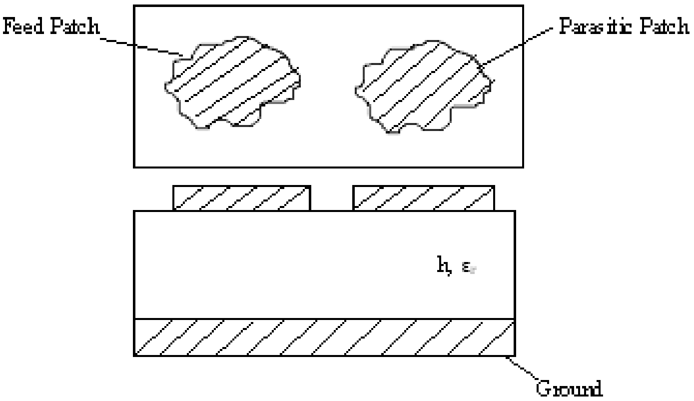

Figure 1: Two gap-coupled microstrip patch antennas.

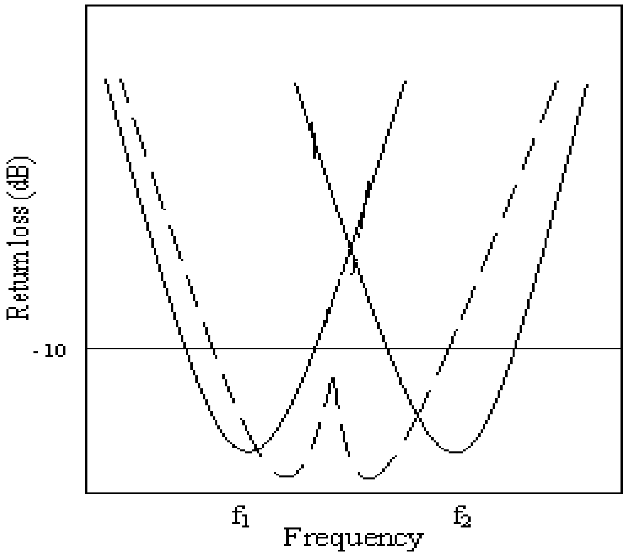

Figure 2: Return loss plot. Dotted line for coupled resonators and continuous line for individual resonators.

3. Research overview of gap-coupled microstrip antennas

The basic configuration of two dipoles gap-coupled to a radiating patch was reported in 1979 [12]. When two patches were gap-coupled to the main patch along the radiating edges, a maximum bandwidth up to 5.1 times that of a single rectangular patch antenna was obtained [13]. This type of parasitic coupling along the non-radiating edges in [14] yielded 4 times the bandwidth. A similar configuration consisting of short circuited quarter wave patches coupled to a half wave patch along the radiating edges yielded approximately 2 times the bandwidth [15]. In [16], two gap coupled rectangular patch antennas are used. In this paper, a rectangular patch is excited and coupled with parasitic elements. The theoretical analysis is performed and the bandwidth of the antenna is improved up to 8 times than the single rectangular patch antenna. In [17], two semicircular gap-coupled microstrip antennas and two triangular gap-coupled microstrip antennas are discussed. In this literature [17], the analysis is carried out using the multiport network model. The semicircular and triangular gap-coupled microstrip antennas yield bandwidth which is more than twice the bandwidth of the corresponding circular and equilateral patches, respectively.

In [13], three rectangular gap-coupled microstrip antennas are used. A two-dimensional approach using the impedance Green's function and segmentation method has been used for analysis. The obtained bandwidth of the antenna is 5 times that of a single rectangular patch antenna. In [18], the structure used in [13] is modified. In this literature [18] various stacked combinations of multiple rectangular patches on thick air dielectric substrate are presented. In all configurations only one rectangular patch at the bottom layer is fed with a co-axial line and other patches are parasitically coupled. A parametric study has been carried out using method-of-moment based IE3D software. The configuration with three rectangular patches stacked on a single feed patch yielded a bandwidth of 830 MHz (25.7%) with more than 10 dB gain within the bandwidth. Higher gain is achieved when three patches are stacked on the three gap-coupled rectangular patches. In [19], a compact broadband antenna is designed and fabricated using a gap-coupled microstrip antenna with photonic band gap. The gap-coupled microstrip antenna consists of a number of parasitic elements which are gap-coupled to driven patch. The measured center frequency of the gap-coupled patch antenna and conventional patch antenna is 2.568 GHz and 2.483 GHz, respectively. The impedance bandwidth has been observed 4 times greater than conventional microstrip patch antenna at VSWR 2 : 1. A photonic band gap has been applied to suppress surface waves propagating on the substrate which improves the radiation pattern and bandwidth.

In [20], a different type of triangular gap-coupled microstrip antenna is presented. In this configuration two triangular patches are kept in such a way that a rectangular structure is formed. A parametric study is carried out using Method of Moment based software. This configuration yields 2.38 times large bandwidth as compared to the equilateral triangular microstrip antenna. In [21], experimental investigations on three hybrid coupled circular microstrip antennas are reported. There, the coupling between the patches is increased by shorting the patches to obtain dual, triple, and wideband responses. This makes this configuration more suitable for wideband applications as compared to the gap-coupled rectangular patches.

4. Numerical modelling of gap-coupled microstrip antennas

The numerical analysis of the antenna is important for the designing of the antenna for various specified parameters. In [22], an expression for the resonant frequency of two gap-coupled circular microstrip patch antennas is derived by using the concept of cavity model and circuit theory. The overall structure is divided into two regions and fields in each region are evaluated from the solution of the appropriate Helmholtz equation for TM modes. Evaluation of the constants using the boundary conditions leads to a transcendental equation and the resonant frequencies for different modes are determined from the solution of the transcendental equation. The equivalent circuit for the gap distance has been utilized. It is shown that such a combination leads to a very accurate model of the gap-coupled circular microstrip antenna and it leads to dual frequency operation with closely spaced resonances. The computed results are compared with the simulated as well as previously reported literatures. The simulation is performed by using the Method of Moment based commercially available simulator IE3D.

In [23], an expression for the resonant frequency of two gap-coupled circular microstrip patch antennas loaded with shorting post is derived by using the similar approach as in [22]. It is shown that such combination leads to a very accurate model of the two gap-coupled circular microstrip antennas loaded with shorting post. The variation of resonant frequency with the gap distance between adjacent edges as well as with the diameter of the shorting post is also analyzed. Ray et al. [24] have designed dual and triple frequency band operation gap-coupled microstrip patch antennas and Ansari et al. [25] have presented the analysis of a gap-coupled stacked annular ring microstrip antenna. The effects of the several geometrical design parameters on the input impedance of stacked short circuited patch antennas have been discussed first in [26] and more thoroughly in [27].

In [28], the concept of coupled microstrip lines [29] is extended for the two gap-coupled circular microstrip patch antennas to analyze the input impedance by using the circuit theory approach and the results are compared with the simulated results. Comparison of these results shows good agreement with the simulated results. In the analysis, the total capacitance of a microstrip patch antenna is taken as parallel plate capacitance and two fringing capacitances for both even and odd modes. Since there is another patch that is the parasitic element in the proposed two gap-coupled circular microstrip patch antennas, so there is another fringing capacitance at the adjacent edge of the patches.

The mutual coupling influences the radiation mechanism of the antennas in both ways, namely, constructive and destructive [30]. In the former case, such coupling is helpful and in the latter case, attempt is to be made to reduce the same effect. Thus, in all cases the estimation of the mutual coupling is important. In [31], the numerical computation of the mutual coupling between two gap-coupled circular microstrip patch antennas has been presented. The mutual admittance is computed by using the cavity model and reaction theorem for two circular patches and the computed results are compared with the reported literature. In [32], the mutual admittance of the two gap-coupled circular microstrip antennas loaded with shorting post is analyzed. The analyzed results are compared with the simulated results.

The gap between the two patches at the point of coupling can be considered as a π–type network [22, 23]. It is shown in Fig. 3. In this figure, $y_n^w(a)$ and $y_n^w(b)$ are the wall admittances of individual patches and $y_n^m(a, b)$is the mutual admittance between the two patches.

The coupled microstrip structures can be characterized for the two modes which are known as odd and even modes [29]. The properties of coupled microstrip patches have been determined by the self and mutual inductances and capacitances between the patches. Under the quasi-transverse electromagnetic mode approximation, the self-inductance can be expressed in terms of self-capacitance by using simple relations. For most of the practical circuits, using symmetric microstrip patches, the mutual-inductance and mutual-capacitance are interrelated to each other, so it is not necessary to determine each separately. Therefore, only capacitance parameters are evaluated for the two gap-coupled circular microstrip patch antennas. The capacitances can be expressed in terms of even and odd modes values for propagation [29].

The total capacitance of the coupled structure can be determined by using Figs. 4 and 5 for even mode and odd mode, respectively. From Fig. 4, the total capacitance for even mode, C_E is given by [29]

$$C_E = C_P + C_F + C_{F'}, \tag{1}$$

where C_P is the parallel plate capacitance between metallic patch and the ground plane and is given by

$$C_P = \frac{\varepsilon_0 \varepsilon_r A}{h}, \tag{2}$$

where A is the surface area of the patch and ε_r is the relative dielectric permittivity of the substrate and ε_0 is the permittivity of free-space. C_F is the fringing capacitance due to edge conductor and given by

$$C_F = \frac{1}{2}\left[\frac{\sqrt{\varepsilon_{eff}}}{cZ_C} - C_P\right], \tag{3}$$

where $c = 3 \times 10^8$ m/s that is velocity of light in vacuum, Z_C is the characteristic impedance and ε_{eff} is the effective dielectric permittivity of the substrate. $C_{F'}$ is the fringing capacitance due to parasitic patch and given by

$$C_{F'} = \frac{C_F}{1 + A\left(\frac{h}{s}\right)\tanh\left(\frac{10s}{h}\right)}\sqrt{\frac{\varepsilon_r}{\varepsilon_{eff}}}, \tag{4}$$

where $A = \exp\left(-0.1\exp\left(2.33 - \frac{2.53C}{2h}\right)\right)$ and C is the circumference of the patch. With the help of Eqs. (1) to (4), the even mode-capacitance of the two gap-coupled circular microstrip patch antennas is calculated.

From Fig. 5, the total capacitance for odd- mode, C_O, is given by [29]

$$C_O = C_P + C_F + C_{gd} + C_{ga}, \tag{5}$$

where C_{gd} is the capacitance between two structures through dielectric region and given by

$$C_{gd} = \frac{\varepsilon}{\pi}\ln\left(\coth\left(\frac{\pi s}{4h}\right)\right) + 0.65C_F\left(\frac{0.02\sqrt{\varepsilon_r}}{s/h} + 1 - \frac{1}{\varepsilon_r^2}\right), \tag{6}$$

and $C_{ga}$is the capacitance between the structures through air and given by

$$C_{ga} = \frac{K(k')\varepsilon_0}{2K(k)}, \tag{7}$$

where $K(k)$ and $K(k')$ are elliptic functions, and $k = \frac{s/h}{s/h+2(C/h)}$ and $k' = \sqrt{1-k^2}$.

Using even mode and odd mode capacitances, the equivalent circuit model of the gap-coupled microstrip structure for both modes can be determined. Using these circuit models, various parameters such as real and imaginary parts of input impedance, return loss, resonant frequencies, bandwidth, etc. can be determined.

5. Types, applications, and challenges

Gap-coupled microstrip antennas may be of various types depends upon the type of used patch [33]. These can be as rectangular gap-coupled microstrip antennas, circular gap-coupled microstrip antennas, triangular gap-coupled microstrip antennas, semi-circular gap-coupled microstrip antennas, elliptical gap-coupled microstrip antennas, square gap-coupled microstrip antennas, hexagonal gap-coupled microstrip antennas, octagonal gap-coupled microstrip antennas, fractal gap-coupled microstrip antennas, etc.

Gap-coupled microstrip antennas are used for multi-frequency operations as well as for increasing the bandwidth of the conventional microstrip antennas. The effect of parasitic patch on the antenna bandwidth is shown in [34]. In [35], using the concept of gap-coupling, the microstrip patch antenna is designed for 77 GHz millimeter band. In [36], authors have presented the novel configurations of compact and broadband coupled microstrip antennas (MSAs). Bandwidths of the proposed antennas are 5.4 – 6.1 times greater than the corresponding conventional MSAs. These antennas consist of a driven patch and another short-circuited parasitic patch. The proposed antennas are numerically investigated using Finite Element Method (FEM) based software (HFSS). Experimental results are also presented and comparison between simulations and measurements are provided. In [37], a novel design of U-slot gap-coupled rectangular microstrip array antenna for triple-band operation is presented. This antenna offers triple bands at 8.24, 8.86, and 11.02 GHz of frequencies.

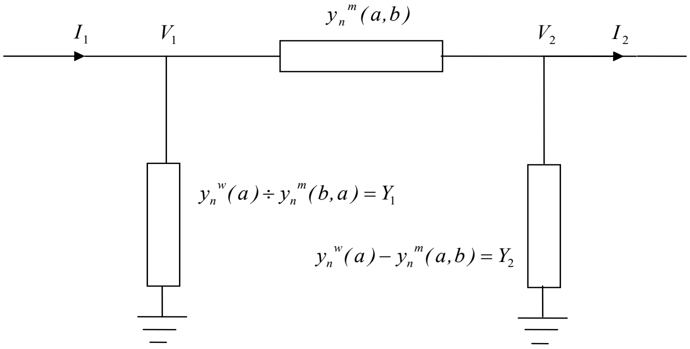

Figure 3: Equivalent circuit diagram of gap between patches.

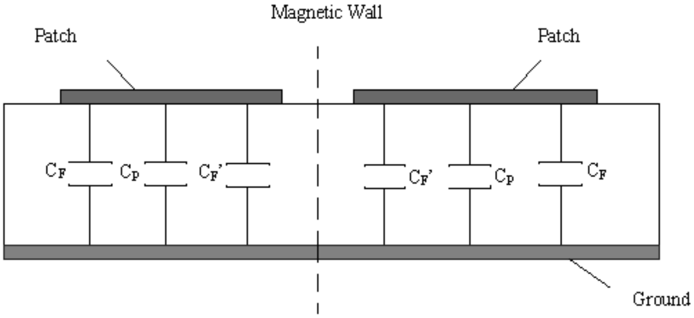

Figure 4: Even-mode capacitances of the two gap-coupled circular microstrip patch antennas.

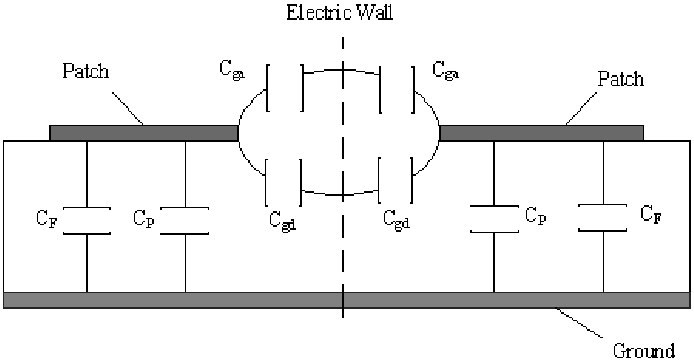

Figure 5: Odd-mode capacitances of the two gap-coupled circular microstrip patch antennas.

In [38], a novel planar microstrip array antenna is proposed and fabricated. This antenna is composed of one active or fed microstrip patch and two parasitic microstrip patches. The two parasitic patches are coupled with active patch via one-dimensional electromagnetic band gap (1D-EBG) structures. 1D-EBG structures, maintaining the resonation of active patch, supply microwave power to parasitic patches, then no feeding circuits are needed and compact antenna is realized. Because of enhancement of coupling between active and parasitic patches, this antenna performs high gain of 10.8 dBi at 5.8 GHz, comparable to ideal three active patches arrays.

As described above, the gap-coupling is the potential method to enhance the bandwidth of the conventional microstrip antennas. For multi-band applications also, the gap-coupling is suitable method. Various structures using different types and sizes of the patches, number of patches, gap-coupled microstrip antennas can be designed for various applications. Gap-coupling along with some other bandwidth enhancement techniques can be used together to produce ultra large bandwidth, and the antennas can be designed for various wideband applications. The numerical modelling of these designed microstrip antennas can also be performed using various techniques such as cavity model, circuit approach, Method of Moment (MoM), FDTD, etc. The consideration of mutual coupling in the analysis of gap-coupled microstrip antennas is also essential. To minimize the coupling effects in the gap-coupled microstrip antennas is also a challenge to researchers.

6. Conclusion

In this paper, a technical survey of gap-coupled microstrip has been presented. The gap-coupled microstrip antennas can be used for wideband as well as multiband applications. The concept of enhancing the bandwidth as well as the concept of dual frequency operation has been explored. The numerical models for the analysis of gap-coupled microstrip antennas have been described. The types of the gap-coupled microstrip antennas based upon the type of patch have been given. The various applications as well as challenges of gap-coupled microstrip antennas are also elaborated in this manuscript.

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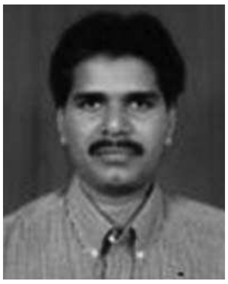

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