A 2-PIN LOADED PATCH AS A MULTIBAND ANTENNA FOR WIRELESS COMMUNICATION

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ABSTRACT

A new microstrip patch antenna, capable of dual or triple band operation is proposed. The patch is circular in shape and is loaded by two shorting pins having a certain angular separation of 2α. The dominant cavity modes of the patch antenna are studied using a developed rigorous theory. It is found that the first three dominant modes of the loaded patch can act as good radiators with distinct resonant frequencies, hence providing dual or triple-band operation. Salient mode characteristics such as the resonant frequency, radiation power, and the radiation quality factors are derived. Numerical results showing the dependence of these parameters on the angular separation angle 2α and the patch geometry are presented and compared with several simulations obtained by Zealand IE3D software.

I. INTRODUCTION

With the growing interest in wireless communication and the emergence of new generations there has been a need to use the same antenna for more than one band. Several approaches have been proposed for single feed dual frequency operation. These include the annular slot antenna with capacitor loading [1], the compact PIFA [2] and the H- microstrip antenna [3]. Here we propose a new patch antenna configuration that can achieve dual or multiband operation. The proposed antenna is a circular patch loaded with two shorting pins as depicted in Fig.1. The case of a circular patch with a single shorting pin has been studied by several authors [e.g.4-6] and is proved to provide a significant size reduction when operated in the dominant mode. However a single pin loaded patch suffers from the necessity to keep close proximity between the pin and the feeding probe, which raises a mechanical difficulty. The use of a patch with two shorting pins with a given angular separation should alleviate this difficulty, besides providing multiband operation with controlled ratio of resonant frequencies.

In this paper we consider a circular patch with two shorting pins. The aim is to deduce the characteristics of the first few cavity modes in terms of their resonant frequencies and their radiation behavior. To our knowledge, no analysis has been presented for this patch configuration. So, we introduce here a rigorous analysis to determine the resonant frequencies, field distribution and radiation character of the dominant modes. In the next section we briefly derive the modal equation for the cavity modes and obtain their modal fields. In section 3, modal radiation fields and power are addressed. We compare numerical results obtained by theory with some simulations performed on the Zealand IE3D software in section 4.

II. CAVITY MODES OF A 2-PIN-LOADED CIRCULAR PATCH

We consider a circular patch of a radius 'a' on a grounded dielectric layer of thickness 'h' and relative dielectric constant 'ε_r' with z axis coinciding with the patch axis. Two thin shorting pins, each of radius 'b' are placed at (r_0, $\phi=\pm\alpha$) as shown in Fig.1. Adopting the cavity model for the patch, the boundary $r=a$ is considered to behave as a magnetic wall. We wish to find the fields and the resonant frequencies of the normal cavity modes in the presence of the two shorting pins. We start by assuming z-oriented currents $I_{1,2}\exp(j\omega_r t)$ flowing in the two pins, where ω_r is the (so far unknown) modal resonant frequency. For even modes (having E_z even function of ϕ), we have $I_1 = I_2 = I$. Conversely, for odd modes, $I_1 = -I_2 = I$. Due to the smallness of the pins radii, the currents can be considered to be concentrated on the axes of the pins.

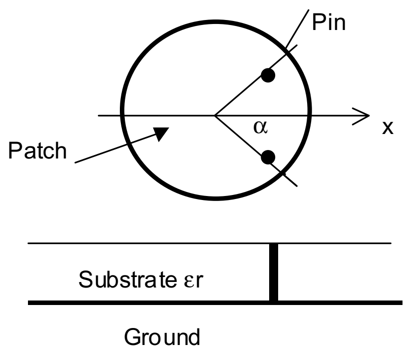

Fig.1: A circular patch, of radius *a* with two shorting pins of radii *b* and angular distance 2α; r_0 is the radial position of the pins.

Following the authors' work in [6], such modal pin currents produce a modal electric field given by:

$$E_z(r,\phi)=\sum_{n=0}^{\infty} E_n \quad J_n(kr) \quad \begin{bmatrix}\cos n\phi \\ \sin n\phi\end{bmatrix} \qquad (1)$$

for $0 \le r \le r_0$, and,

$$=\sum_{n=0}^{\infty} E_n J_n(kr_0)\begin{bmatrix}\cos n\phi \\ \sin n\phi\end{bmatrix}\frac{J_n(kr)Y_n'(ka)-Y_n(kr)J_n'(ka)}{J_n(kr_0)Y_n'(ka)-Y_n(kr_0)J_n'(ka)} \qquad (2)$$

for $r_0 \le r \le a$,where the *cos* and *sin* functions relate to even and odd modes about ϕ=0 respectively. The functions $J_n(.)$ *and* $Y_n(.)$ are the Bessel functions of first and second kind; the prime denotes differentiation with respect to the argument and $k=\omega_r\sqrt{\varepsilon_r}/c$, with *c* the wave velocity in free space. Note that E_z is readily continuous at $r=r_0$, while $H_\phi \propto \partial E_z/\partial r = 0$ *at* $r=a$ satisfying the boundary condition at the magnetic wall. Next, we use the discontinuity of H_ϕ due to the pin currents at $r=r_0$. The latter can be expressed as:

$$J_z(r,\phi)=(I/r_0)\delta(r-r_0)\left[\delta(\phi-\alpha)\pm\delta(\phi+\alpha)\right]$$
$$=(2I/\pi r_0)\delta(r-r_0)\sum_{n=0}^{\infty}\chi_n\begin{pmatrix}\cos n\phi\cos n\alpha \\ \sin n\phi\sin n\alpha\end{pmatrix} \qquad (3)$$

and the discontinuity of H_ϕ by this current leads to the determination of the coefficients E_n as:

$$E_n=-j\omega\mu_0 I\chi_n\begin{pmatrix}\cos n\alpha \\ \sin n\alpha\end{pmatrix}\frac{J_n(kr_0)Y_n'(ka)-J_n'(ka)Y_n(kr_0)}{J_n'(ka)} \qquad (4)$$

where $\chi_n=1$ for $n \ge 1$, and $\chi_0=1/2$ for $n=0$.

Now, the modal equation for the resonant frequency is obtained by imposing the boundary condition of vanishing E_z at the pin surface. Since the pin radius '*b*' is assumed very small relative to the field variation, we are allowed to satisfy the vanishing E_z at one line on the pin surface; say the line ($r=r_0-b$, $\phi=\alpha$) to get, after some manipulations:

$$Y_0(kb)\pm Y_0(kd)-4\sum_{n=0}^{\infty}\chi_n\left[J_n(k(r_0-b)J_n(kr_0)\right]$$
$$\begin{Bmatrix}\cos^2\alpha \\ \sin^2\alpha\end{Bmatrix} \quad Y_n'(ka)/J_n'(ka)=0 \qquad (5)$$

where *d* is the distance between the two pins and the upper/ lower terms correspond to even/odd modes respectively. The resonant frequencies are obtained by solving the modal equation (5) for the set of discrete values of $ka=\omega_r \cdot a\sqrt{\varepsilon_r}/c$, with $\omega_r=\omega_{r1}$, ω_{r2}… which are the modal resonant frequencies. Universal curves for the normalized resonant frequency ka of the first two even modes and the first odd mode are given versus half pin separation angle 'α', for fixed r_0/a and *b/a* in Fig.2. These modes are the dominant modes that are expected to have good radiation efficiency. Here '*a*' should be taken as the effective radius of the patch after accounting for field fringing. It is seen that dual or triple band operation is possible if the feed excites efficiently the corresponding modes. It is useful to note here that the placement of the feeding probe in the plane $\phi=0$ will excite the even modes only, leading to dual band operation. Setting the feed at $\phi_f \neq 0$ will excite the odd mode as well. In Fig 3, we show the ratio of the resonant frequency of the first two even modes versus the angle α. It is seen that dual band operation with frequency ratio ranging

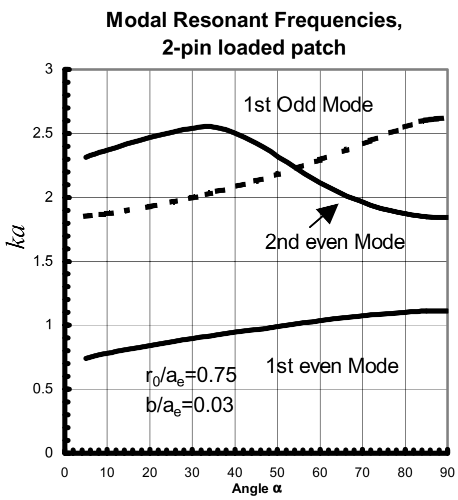

Fig.2: Normalized resonant frequency *ka* for first 2 even modes and the first odd mode versus angle α. Here b/a_e=0.03 and r_0/a_e=0.75.

from ~ 1.6 to 3 is possible by the right choice of 'α'. For example dual band operation at the second generation GSM (2G) centered at 925 MHz and the third generation (3G) IMT-2000 centered at 2035 MHz is possible by the choice α=56°. In this case, the effective patch radius =35.2mm on a substrate with ε_r=2.2. Note that the actual patch radius will be less because of field fringing. In the above example, the required radius *a*=31.6mm when the substrate height *h*=7. 04 mm. Another point that can be inferred from Fig.2 is that the first even mode, which is the dominant cavity mode of the patch, possesses the least resonant frequency. This means that for a given operating frequency, this mode provides patch area saving. This agrees with results obtained earlier [6] for the dominant mode of a single pin loaded patch.

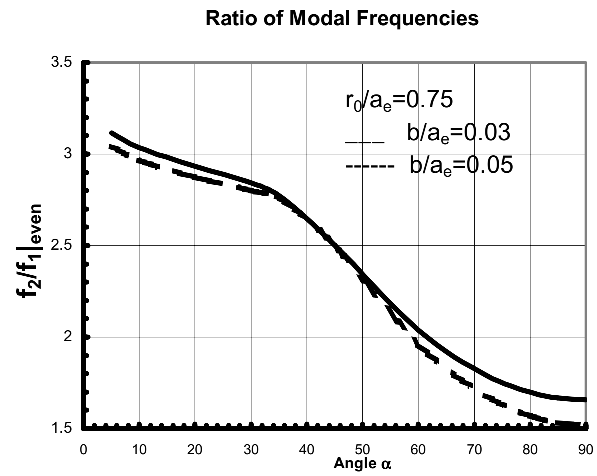

Fig.3 : Ratio of resonant frequencies of the second to first even modes versus angle α.

III. RADIATION CHARACTER OF THE MODES

In this section we derive the radiation fields and power of each of the natural modes of the patch. The starting point is to find the aperture field E_z at *r=a*. Using (2) and (4) with *r=a*, we get:

$$E_{za}(a,\phi) = \sum_{n=0}^{\infty} E_{an} \begin{pmatrix} \cos n\phi \\ \sin n\phi \end{pmatrix} = \frac{-2\omega_r \mu_0 I}{\pi \quad ka} \sum_{n=0}^{\infty} \chi_n \frac{J_n(kr_0)}{J_n'(ka)} \begin{pmatrix} \cos n\alpha \cos n\phi \\ \sin n\alpha \sin n\phi \end{pmatrix} \tag{6}$$

where the E_{an} factors are defined by (6) for even and odd modes. The fields excited by this aperture field in the outer region $r > a$ and $z > h$ have been derived in [6]. In the far zone fields are derived as:

$$E_\theta(R,\theta,\phi) \approx -k_0 a h (e^{-jk_0 R}/R) \sum_n j^n E_{an} J_n'(k_0 a \quad \sin\theta) \begin{pmatrix} \cos n\phi \\ s\sin n\phi \end{pmatrix} \tag{7}$$

$$E_\phi(R,\theta,\phi) = k_0 ah\,(e^{-jk_0R}/R)\quad\cos\theta$$

$$\cdot\sum_n j^n E_{an}\, n \frac{J_n(k_0 a\sin\theta)}{k_0 a\sin\theta}\begin{pmatrix}\sin n\phi\\ -\cos n\phi\end{pmatrix}\qquad(8)$$

where (R,θ,ϕ) are the usual spherical coordinates, $k_0=\omega\sqrt{\mu_0\varepsilon_0}$,and $k_0R>>1$. The total radiated power is given by :

$$P_r = \frac{\pi h^2}{\omega_r\mu_0 a}\sum_{n=0}^{\infty}(|E_{an}|^2/\chi_n)\, I;\ where$$

$$I=\int_{g=0}^{k_0}\left[k_0^2a^2\frac{g}{\sqrt{k_0^2-g^2}}J_n'^2(gr)+\frac{n^2\sqrt{k_0^2-g^2}}{g}J_n^2(gr)\right]dga\qquad(9)$$

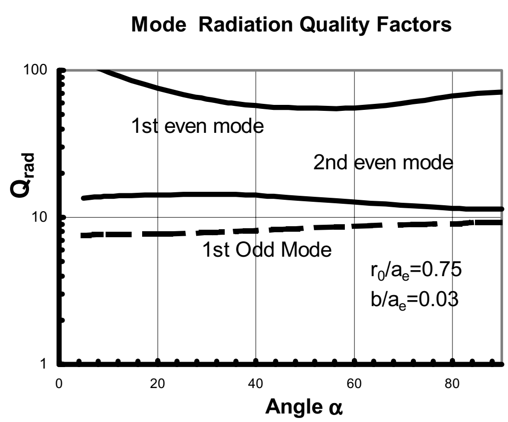

Fig.4: Radiation Quality factor of the first two even modes and the first odd mode.

The integration is taken over the radial wavenumber g in the range $\{0\text{-}k_0)$ and can be readily evaluated numerically. The sum can be truncated at $n=3$ or 4 with no significant error. The energy stored 'W' in the patch cavity for a given mode at resonance can be obtained by integrating εE_z^2 in (1-2) over the cavity volume. Now, the mode radiation quality factor Q_r is obtained as $Q_r=\omega_r W/P_r$. The quality factors for the first two even modes and the first odd mode of a 2-pin loaded patch are plotted versus the angle α in Fig.4. It is clear that the quality factor of the first even mode is significantly higher than those of the second even and first odd mode. This means that the first even mode is a less efficient radiator than the other two modes.

IV. SIMULATION RESULTS

In order to support the presented theory several simulations are carried out using Zealand IE3D software. The geometry considered is that shown in Fig.1 and the geometry parameters are summarized for four simulation cases in Table 1. The magnitude of the reflection coefficient S_{11}, relative to a 50 Ω feed line, is shown in dB versus frequency in Figures 5-7. The angle α is taken equal to 30^0 in Fig.5, 60^0 in Fig. 6, and 72^0 in Fig.7. In all simulations, ε_r =2.2, r_0/a_e =0.75, b/a_e =0.03, and h/a_e=0.2, where a_e is the effective patch radius taking the field fringing into account [7].

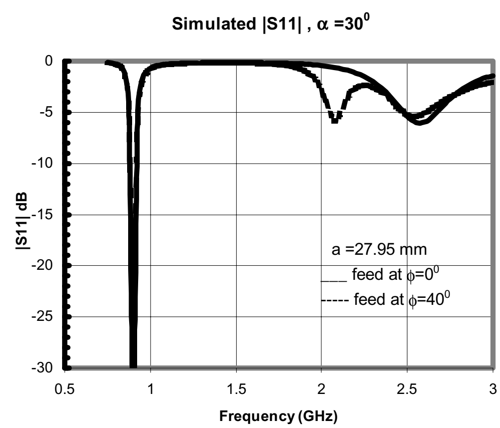

Fig.5: |S11| in dB for α=30^o and two feed positions

We have chosen the actual patch radius such that the first mode resonates at 925 MHz. With α =30^0, the feed is located at $(r_0,\phi_f=0)$ in for the solid curve where the first two even modes appear at ~900 MHz and 2575 MHz. As expected, no odd mode is excited in this case since the feed is located at a null for these modes. When the feed is moved to $(r_0, \phi_f = 40^0)$ for the dashed curve in Fig.5, the first odd mode is excited at a resonant frequency $f_{1,odd}$ =2062 MHz, in addition to the first two even modes.

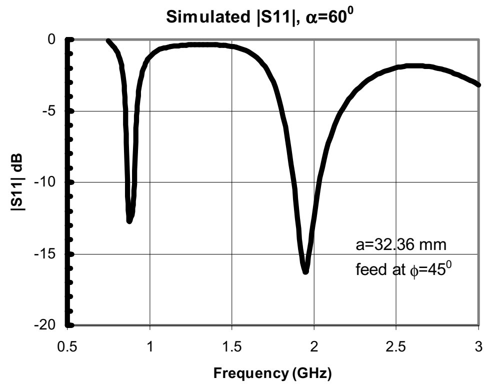

Fig.6: |S11| for α=60^o and feed at (r_0,45^o)

Next consider the simulations for α=60^0 and 72^0 in Fig. 6 and 7 respectively. For such large values of α, the modal currents are small near the axis ϕ=0. So, if the feed were located at ϕ=0, the input impedance would be too high to achieve matching. We therefore choose ϕ_f =45^o and 50^o in Fig.6 and 7. In Fig.6 for α=60^0, only two modes appear since the second even mode and the first odd mode have their resonant frequencies so close (see Fig.2) that they appear as one mode. For α=72^0, three modes appear with the odd mode having a resonant frequency higher than that of the second even mode in agreement with theoretical results of Fig.2.

The simulated resonant frequencies are compared with the theoretical values in the first row of Table 2 and it is seen that the difference between simulated and theoretical results ranges from 0.3% and 3%. This is largely caused by the definition of the effective patch radius a_e based on electrostatic analysis [7] while it is expected that it must change with frequency from one mode to another.

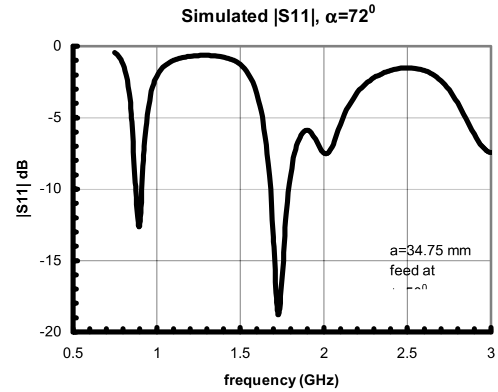

Fig.7: |S11| for α=72^o and feed at (r_0,50^o)

It is clear that for the chosen feed location (ϕ_f=50^0), the odd mode is not well matched. There was no attempt to optimize the feed location, but it is probably difficult to achieve matching for the three modes with a single feed. For example, it may be necessary to use a matching circuit for the odd mode in Fig.7. Matching techniques as described in [8] may then be applied.

Considering the bandwidths of the modes in Fig.6, we find that the –10 dB bandwidth of the 900 MHz mode is about 36 MHz which amounts to 4%. The bandwidth of the second mode is about 175 MHz around a center frequency of 1950 MHz which is

Table 1
Geometrical parameters of Simulation cases

No.	Angle α	a (mm)	$a_{effective}$ (mm)	h(mm)	Feed at (r_f,ϕ_f)
1	30	27.95	31.11	6.19	(23.3,0^0)
2	30	27.95	31.11	6.19	(23.3,40^0)
3	60	32.36	36.04	7.21	(27.0,45^0)
4	72	33.77	37.61	7.52	(28.2,50^0)

equivalent to ~ 9%. These bandwidths are adequate for dual band operation for the 2G GSM and IMT-2000 provided that the second center frequency is shifted to 2035MHz by changing α to 56^0 as stated earlier.

Table 2
Theoretical versus Simulated results on modal resonant frequencies

Angle α^0	f_{1e}^{TH}/f_{1e}^{SIM} (MHz)	f_{2e}^{TH}/f_{2e}^{SIM} (MHz)	f_{1o}^{TH}/f_{1o}^{SIM} (MHz)
30^0	925/900	2629/2575	2068/2062
60^0	925/912	1887/1937	2047/1937
72^0	925/900	1661/1712	2088/2025

V. CONCLUSIONS

The cavity modes on a circular microstrip patch antenna loaded by 2 shorting identical pins have been rigorously treated. The resonant frequencies of the even and odd modes are obtained as the solution of a derived modal equation and it is found that the lowest two even modes and the first odd mode provide the possibility of dual or triple band operation. The pin separation angle 2α acts a controlling parameter for the modal resonant frequencies and therefore determines the ratios between the operating bands in dual or triple band operation. Simulations performed on the Zealand IE3D software support the theoretical results. As expected, the position of the feeding probe determines the relative excitation of modes and input impedance at their resonant frequencies. Results show that it is feasible to have a dual band operation with good matching using a single feed. It may be difficult though to achieve good matching for the three modes in a triple band operation, whence it may be necessary to use some matching technique at one of the modes. The results are pertinent to antenna design for wireless communication.

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