0.7687GHz, corresponding to the anti-resonant state inside the coaxial line. In addition, the low slot is already as wide as 0.12λ at $f = 1.5$GHz. This demonstrates the good adaptability of our model.

Conclusion: An efficient model extended from the fixed-gap model is proposed. The calculated results are in good agreement with experiments. This model is easy to combine with MoM and converges better than the one cell source model. Keeping the gap width unchanged, considering the mutual coupling, and using the non-uniform electric fields, this more realistic model is appropriate for antennas with multiple wide slots.

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Fast frequency-sweep analysis of microstrip antennas on dispersive substrate

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A fast technique that combines the method of asymptotic waveform evaluation (AWE) and the hybrid finite-element boundary-integral (FE-BI) method is introduced for the analysis of cavity-backed microstrip patch antennas residing on a dispersive substrate. Numerical examples are given to demonstrate the accuracy and efficiency of the technique.

Introduction: The hybrid finite-element boundary-integral (FE-BI) method [1] is a powerful numerical technique for the analysis of cavity-backed microstrip patch antennas residing on a dielectric substrate. Like any other frequency-domain based method, the FE-BI method must repeat its analysis at several frequency points to obtain the solutions over a specified frequency band. Since microstrip patch antennas are resonant structures, their characteristics such as input impedance vary drastically with frequency. As a result, the frequency increment must be sufficiently small to generate a smooth frequency response curve. This is computationally expensive, especially when many designs have to be evaluated. Recently, a fast technique was presented for alleviating this difficulty [2]. In this technique, the method of asymptotic waveform evaluation (AWE) was applied to the solution of the FE-BI matrix equation. It was shown that the AWE method could speed up the frequency-sweep analysis by more than an order of magnitude. In this Letter, we extend the technique to the analysis of microstrip patch antennas residing on a dispersive substrate, the permittivity of which is a function of frequency.

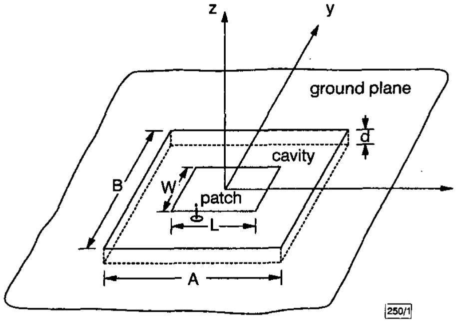

Fig. 1 *Cavity-backed microstrip patch antenna*

Formulation: Consider a cavity-backed microstrip patch antenna recessed in a ground plane (Fig. 1). It has been shown [1] that the electric field inside the cavity and over the aperture can be found by seeking the stationary point of the functional

$$\begin{aligned} F(\mathbf{E}) = \frac{1}{2} \iiint_V \left[\frac{1}{\mu_r} (\nabla \times \mathbf{E}) \cdot (\nabla \times \mathbf{E}) - k^2 \epsilon_r \mathbf{E} \cdot \mathbf{E} \right] dV \\ + \iiint_V \left[jkZ\mathbf{J}^{int} \cdot \mathbf{E} - \frac{1}{\mu_r} \mathbf{M}^{int} \cdot (\nabla \times \mathbf{E}) \right] dV \\ - k^2 \iint_S \mathbf{M}(\mathbf{r}) \cdot \left[\iint_S \mathbf{M}(\mathbf{r}') G(\mathbf{r}, \mathbf{r}') dS' \right] dS \\ + \iint_S \nabla \cdot \mathbf{M}(\mathbf{r}) \left[\iint_S G(\mathbf{r}, \mathbf{r}') \nabla' \cdot \mathbf{M}(\mathbf{r}') dS' \right] dS \quad (1) \end{aligned}$$

where V denotes the volume of the cavity and S denotes its aperture, $\mathbf{M} = \mathbf{E} \times \hat{z}$ is the equivalent magnetic current over the aperture, k is the free-space wavenumber, Z is the free-space wave impedance, $G(\mathbf{r}, \mathbf{r}')$ denotes the free-space Green's function, and $\mathbf{J}^{int}$ and $\mathbf{M}^{int}$ denote the electric and magnetic currents of the antenna feed.

The dielectric substrate is characterised by its relative permittivity ϵ_r and permeability μ_r. For a dispersive substrate, ϵ_r and μ_r can be a function of frequency. For simplicity, we assume that μ_r is a constant and only ϵ_r varies with frequency. However, the analysis can easily be extended to the case when both ϵ_r and μ_r vary with frequency. There are several models that describe dispersive material and all of them can be employed in this analysis. When the Debye model [3] is used, the relative permittivity of the substrate can be written as

$$\epsilon_r(\omega) = \epsilon_r'(\omega) - j\epsilon_r''(\omega) = \epsilon_{r\infty}' + \frac{\epsilon_{rs}' - \epsilon_{r\infty}'}{1 + j\omega\tau_e} \quad (2)$$

where ϵ'_{rs} denotes the static dielectric constant, $\epsilon'_{r\infty}$ is the optical dielectric constant, and τ_e is a relaxation time constant related to the original relaxation time constant τ by

$$\tau_e = \tau \frac{\epsilon_{rs}' + 2}{\epsilon_{r\infty}' + 2} \quad (3)$$

The application of the finite element discretisation to eqn. 1 yields the matrix equation

$$A(k)E(k) = B(k) \quad (4)$$

where A is a partly sparse and partly full symmetric matrix, E is a vector representing the discretised electric field, and B is the excitation vector related to the antenna feed. Eqn. 4 can be solved over a specified bandwidth efficiently using the AWE method [4]. In this method, $E(k)$ is first expanded into a Taylor series. The expansion coefficients are then determined by moment matching, which requires the inversion of matrix A and the calculation of the derivatives of matrix A only at the expansion point. The derivatives are contributed by the frequency dependence of k and ϵ_r. Once the coefficients are determined, the Taylor series is converted into a Padé rational transfer function, which has a larger radius of convergence. In the case where one expansion point is not sufficient to cover the desired frequency band, multiple expansion points can be used. These points can be selected automatically using a binary search algorithm described in [5].

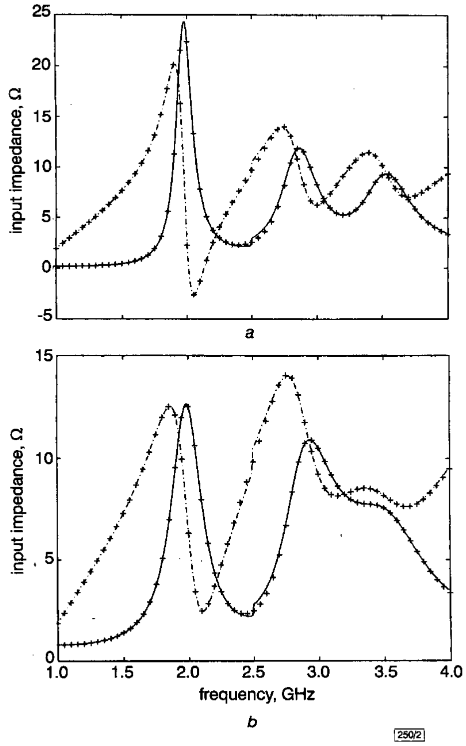

Fig. 2 *Input impedance against frequency for cavity-backed antenna residing on dispersive substrate*

a Without impedance load
b With 50Ω resistor load
—— AWE, resistance
-+-+- direct calculation
-·-·- AWE, reactance

Results: The example used to demonstrate the accuracy and efficiency of the proposed method is a 5.0cm × 3.4cm rectangular patch antenna residing on a dispersive substrate having thickness t = 0.0877cm. Without loss of generality, we assume that $\epsilon'_{rs} = 2.17$, $\epsilon'_{r\infty} = 1.0$ and $\tau = 7.96$ps/rad. As a result, as the frequency varies from 1 to 10GHz, the real part of the relative permittivity varies from 2.16 to 1.79 and the imaginary part varies from -0.081 to -0.55. The substrate is housed in a 7.5cm × 5.1cm rectangular cavity recessed in a ground plane. The patch is excited by a current probe applied at $x_f = 1.22$cm and $y_f = 0.85$cm. Fig. 2*a* shows the input impedance of the antenna from 1 to 4GHz. Fig. 2*b* gives the input impedance when a 50Ω impedance load is placed at x_L = -2.2 cm and y_L = -1.5cm. It can be seen clearly that the AWE solution agrees very well with the direct solution obtained by solving eqn. 4 at each frequency. The number of unknowns used in this calculation is 1741. With a frequency increment of 0.05GHz, for the direct calculation approach 4013.2s is required to obtain the solution. In contrast, the AWE method produces an accurate solution with 0.01GHz increments over the entire band in 261.2s.

Conclusion: A fast technique is described for the analysis of cavity-backed microstrip patch antennas residing on a dispersive substrate. The technique applies the AWE method to the hybrid FE-BI solution of the physical problem. It is shown that the AWE method can accurately account for the dispersive effect of the substrate and speed up the analysis by more than an order of magnitude.

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Wideband L-probe-feed patch antenna with dual-band operation for GSM/PCS base stations

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A dual-band microstrip composed of two patches and two L-probes is proposed. The antenna displays wide-bandwidth characteristics and can be implemented as a dual-mode GSM/PCS base station antenna.

Introduction: Different types of dual-band microstrip antenna with a frequency ratio of 2 have been proposed. By inserting a shorting pin close to the feed position [1], a dual-band characteristic can be obtained. Another technique for generating dual-frequencies in a microstrip antenna is the use of a printed bow-tie antenna [2]. The weakness of these two antennas is their narrow bandwidth. Recently, a novel feeding technique for thick microstrip antennas employing an L-shaped probe [3] has been successfully developed. A bandwidth of > 30% can be achieved for a single-patch antenna. In this Letter, a dual-patch microstrip antenna excited by two L-probes is investigated for dual-band operation. It can potentially be used as a base station antenna for GSM/PCS cellular networks.

Antenna structure: The geometry of the antenna, which operates at both 953.5MHz (f_1) (lower band) and 1.7855GHz (f_2) (upper band), is shown in Fig. 1. The dual-patch antenna is composed of two rectangular patches of different sizes. Two L-shaped probes are connected together to form a feed structure for the dual-probe antenna. The lower-band patch with sides l_1 = 102mm (0.312 λ_1) and w_1 = 110mm (0.336 λ_1) is supported by a foam layer of thickness H_1 = 45.5mm (0.139 λ_1). The effect of the two slots of width 2mm and length 90mm is to suppress the excitation of the TM_{20} mode that would influence the radiation pattern in the upper-band. These slots are located $l_1/4$ from the patch edges. The upper-band patch is a square patch with sides l_2 = 37mm (0.227 λ_2). It is supported by foam. The resonant length of this patch is less than that of an isolated patch operated at the same frequency. This is probably due to the coupling effect of the lower-band patch. The two patches are excited in TM_{10} mode by the feed structure, which is constructed by connecting two L-shaped probes together. The dimensions of the composite antenna are shown in Fig. 1.

Measured results: Fig. 2 shows the measured return loss curve of the antenna. It is observed that both lower and upper bands achieve wide impedance bandwidth ($S_{11} \leq -10$dB) of 20.8 and