Dielectric-based leaky-wave antenna for high gain using a printed surface-wave source

S.K. Podilchak, A.P. Freundorfer, Y.M.M. Antar and S.F. Mahmoud

A multilayer leaky-wave antenna (LWA) is presented for microwave and millimetre-wave frequencies. By placing two superstrate dielectric layers on top of a base grounded dielectric slab, a practical resonant cavity structure can be realised for high gain at 17.39 GHz. The compact 6 × 6 cm LWA is fed by a printed surface-wave source integrated in the bottom ground plane. Measured gain values are greater than 11 dBi at broadside with half power beam less than 7°. The presented low cost and low profile LWA may be useful for radar applications and surveillance systems where lightweight and compact antenna designs are of interest.

Introduction: The proposed planar antenna was realised by a three-layered stack-up of dielectric substrates [1–3] with a slotted surface-wave (SW) source [4–7] etched in the bottom ground plane as shown in Figs. 1 and 2. The multilayer structure can be defined as a type of resonant cavity-based leaky-wave antenna (LWA). Radiation into the far field is achieved by radially excited leaky-wave (LW) modes with propagation away from the top air–dielectric interface [2, 3]. Measured and simulated beam patterns along with calculated LW phase and attenuation constants and radiated powers are shown in Figs. 3 and 4, respectively.

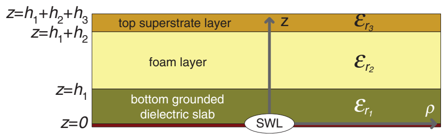

Fig. 1 *Illustrated cross-section for considered LWA*

Three distinct layers are shown with top dielectric defined as superstrate cover ($\epsilon_{r_3} = 30$)

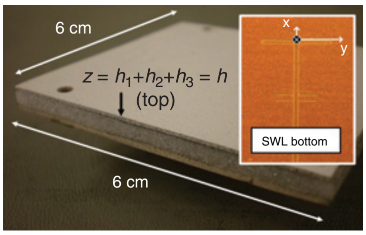

Fig. 2 *Realised multilayer antenna defined by stack-up of low-loss dielectric materials*

6 × 6 cm cavity-based LWA is fed by non-directive SWL integrated in bottom ground plane and can define printed, magnetic dipole source

To the authors' knowledge this is the first time such a planar LWA using a printed SW source has been fabricated, measured and numerically analysed. In addition, the compact and lightweight characteristics of the proposed structure make antenna concealing quite feasible. Applications include low-cost sensors and antennas for radar systems and surveillance.

Antenna design and feed configuration: Classic feeding techniques for such a three-layer LWA design can be problematic at microwave and millimetre-wave frequencies. However, a printed surface-wave launcher (SWL) source in the ground plane is used for the antenna under study that has shown much promise for other single-layer, planar LWA designs [5–7]. Essentially the bidirectional SW field distributions generated by the non-directive SWL [7] are perturbed by the added substrate layers and a leaky, waveguiding structure can be achieved.

The dielectric-based LWA was realised by a base GDS (Rogers Corporation, RT/duroid 6010LM, $\epsilon_{r_1} = 10.2$ rated, $h_1 = 1.27$ mm), a foam layer (Evonik Industries, Rohacell, $\epsilon_{r_2} = 1$, $h_2 = 3.0$ mm), and a top superstrate cover (Emerson & Cuming, ECCOSTOCK HIK 500, $\epsilon_{r_3} = 30$, $h_3 = 0.84$ mm). All utilised materials were commercially available and of low loss (rated tan δ values were less than 0.0023). Initially, a non-directive SWL source was etched in the centre of the bottom ground plane and the top dielectric layers were bonded to the base GDS using an adhesive spray (3M Fastbond 77). The non-directive SWL (with a main slot length of 2.5 mm) was fed by a 50 Ω coplanar waveguide transmission line from the substrate periphery and secondary tuning slots were also included for low reflection losses [6, 7]. In addition, high gain values are expected for this LWA structure [1, 2] since $h_3\sqrt{\epsilon_{r_3}}/\lambda_0 \simeq 1/4$ at 17.39 GHz.

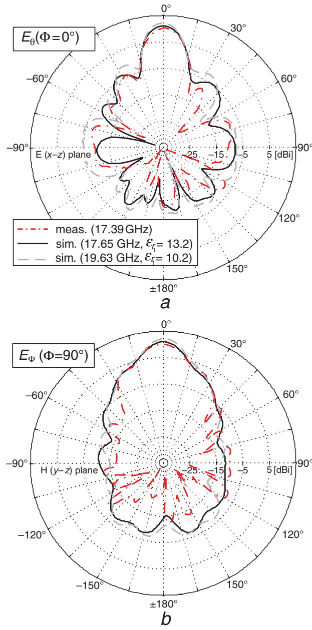

Fig. 3 *Measured $E_\theta(\phi = 0°)$ and $E_\phi(\phi = 90°)$ gain patterns at 17.39 GHz in E(x-z) and H(y-z) planes*

Results compared to two simulation models using Ansoft HFSS; rated and varied base dielectric constant, $\epsilon_{r_1} = 10.2$ and $\epsilon_{r_1} = 13.2$, respectively

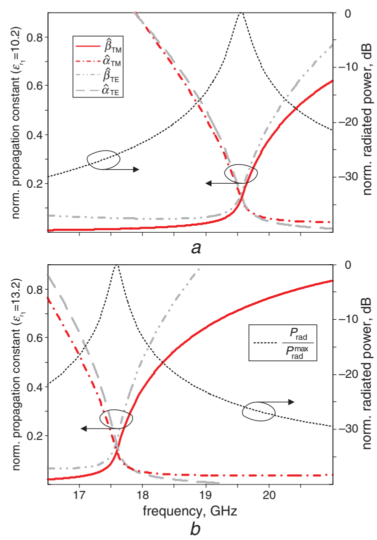

Fig. 4 *Computed LW radial wavenumbers (normalisation with respect to k_0, $\widehat{\beta} = \beta/k_0$ and $\widehat{\alpha} = \alpha/k_0$, for both TM_z and TE_z modes) and radiated powers, P_{rad}, for investigated LWA*

a $\epsilon_{r_1} = 10.2$
b $\epsilon_{r_1} = 13.2$

Analysis of leak-wave antenna structure: The main driven slot of the SWL can be modelled as an ideal magnetic dipole and fields generated by this source may be determined by a spectral-wave analysis [8] resulting in closed-form expressions for the *z*-oriented electric and magnetic field vectors, E_z and H_z. Propagation in the traverse *z*-direction can be characterised by $k_{z_i}^2 = k_i^2 - k_\rho^2$, with $k_i^2 = \omega^2\mu_i\epsilon_i$, $\mu_i = \mu_{r_i}\mu_0$, and $\epsilon_i = \epsilon_{r_i}\epsilon_0$. The subscript *i* denotes the *i*th dielectric layer, with $i = 0$ defining the air region above the top air–dielectric interface for $z \geq h_1 + h_2 + h_3 = h$. Both TM_z and TE_z wave types can be analysed.

Complex radial wavenumbers $k_\rho = k_0\widehat{k}_\rho = \beta - j\alpha$ define LW propagation along the planar guiding surface [2, 3] with the TM_z and TE_z field components generating the observed radiation patterns in the far field for the corresponding E(x–z) and H(y–z) planes, respectively.

Accurate knowledge of these field components may be useful to predict the radiation behaviour of the proposed LWA. For instance, TM_z and TE_z fields can be derived in integral form in the top air region as

$$E_{z,air} \simeq K\frac{\partial}{\partial x}\int_0^\infty J_0(k_\rho\rho)f_{air}e^{-jk_0(z-h)}k_\rho\, dk_\rho/k_{z_1}, \quad \text{and}$$
$$H_{z,air} \simeq \frac{K}{\omega\mu}\frac{\partial}{\partial y}\int_0^\infty J_0(k_\rho\rho)g_{air}e^{-jk_0(z-h)}k_\rho\, dk_\rho \tag{1}$$

where K is the magnetic moment of the slot source (in V m) and J_0 is the Bessel function of the first kind (order 0). In the analysis the time-dependent terms ($e^{+j\omega t}$) are suppressed throughout. The functions f_{air} and g_{air} characterise the aperture fields on the guiding surface and have complex poles which correspond to the TM_z and TE_z LW modes of the analysed high-gain planar LWA. A detailed description of the radial phase (β_{TM} and β_{TE}) and attenuation constants (α_{TM} and α_{TE}) is essential to a systematic design procedure. Once these complex radial wavenumbers are known, the beam direction can be determined along with the corresponding frequencies for high gain.

By successive application of the boundary conditions that exist at the interfaces between the dielectric layers and the air region, the functions f_{air} and g_{air} can be further established. This iterative process can be simplified by generating a transmission matrix describing the continuity of $\epsilon_i E_z$ and $\partial E_z/\partial_z$ at the respective boundary for TM waves. Analogously, the continuity of the $\mu_i H_z$ and $\partial H_z/\partial_z$ terms for TE waves. Closed-form expressions can be determined for f_{air} and g_{air}, respectively, where $f_{air} = jk_{z_1}/(CX - AY)$ and $g_{air} = \mu_0/(\overline{D}\,\overline{X} - \overline{B}\,\overline{Y})$ with

$$\begin{aligned}
A &= \cos\psi_1\cos\psi_2 - (\epsilon_2 k_{z_1}/\epsilon_1 k_{z_2})\sin\psi_1\sin\psi_2\\
B &= (\epsilon_1/k_{z_1})\sin\psi_1\cos\psi_2 + (\epsilon_2/k_{z_2})\sin\psi_2\cos\psi_1\\
C &= -(k_{z_1}/\epsilon_1)\sin\psi_1\cos\psi_2 - (k_{z_2}/\epsilon_2)\sin\psi_2\cos\psi_1\\
D &= \cos\psi_1\cos\psi_2 - (\epsilon_1 k_{z_2}/\epsilon_2 k_{z_1})\sin\psi_1\sin\psi_2\\
X &= \epsilon_0\cos\psi_3 + j\epsilon_3(k_{z_0}/k_{z_3})\sin\psi_3, \quad \text{and}\\
Y &= k_{z_3}(\epsilon_0/\epsilon_3)\sin\psi_3 - jk_{z_0}\cos\psi_3
\end{aligned} \tag{2}$$

with transverse phase accrual defined by $\psi_i = k_{z_i}h_i$ in each layer. The functions $\overline{B}$, $\overline{D}$, $\overline{X}$ and $\overline{Y}$ are equivalent to B, D, X, and Y but with all the ϵ_i terms replaced by μ_i for the appropriate ith layer ($\mu_i = \mu_0$ for the realised LWA since non-magnetic materials were utilised in the antenna fabrication, $\mu_{r_i} = 1$). Furthermore, the spectral functions f_{air} and g_{air} can be approximated for broadside radiating frequencies, namely $f_{air} \simeq g_{air}\sqrt{\epsilon_{r_1}} \simeq \epsilon_{r_1}\sqrt{\frac{\epsilon_{r_3}}{\epsilon_{r_2}}}$. This simplification suggests basic design strategies for maximising field strength on the aperture and thus suitable conditions for achieving high gain at broadside; ie. ϵ_{r_3} and ϵ_{r_1} should be much greater than ϵ_{r_2}.

Using (1) and (2) the resultant E_θ and E_ϕ far-field radiation patterns can be determined using the stationary phase method of integration [8]. Radiated power from the antenna can also be obtained by integrating the intensity of these far-field components over the solid angle of a large sphere, resulting in

$$P_{rad} = \frac{(Kk_0)^2}{4\pi\eta_0}\int_{\theta=0}^{\pi/2}\left(\frac{|f_{air}|^2}{\epsilon_{r_1} - \sin^2\theta} + |g_{air}|^2\right)\cos^2\theta\sin\theta\, d\theta \tag{3}$$

Results and discussion: Initially simulations were completed in HFSS for the described LWA. A pencil beam with maximum gain at broadside was provided at 19.63 GHz, as illustrated in Fig. 3. Calculated complex wavenumbers predict similar behaviour at 19.6 GHz since $\beta_{TM} \simeq \beta_{TE} \simeq \alpha_{TM} \simeq \alpha_{TE}$, as shown in Fig. 4*a* with radiated powers, P_{rad}, achieving maximum values.

It should be noted that a downward frequency shift was observed for the realised LWA structure, and maximum gain values were measured at 17.39 GHz. To investigate this discrepancy a parametric analysis was completed in HFSS. By increasing the relative dielectric constant of the bottom layer to 13.2 (from the rated 10.2 by Rogers Corporation, at 10.0 GHz), while maintaining all other parameters, the simulation frequency for high gain was reduced to 17.65 GHz. Gain patterns are compared in Fig. 3 and agreement can be observed in both principal planes for these two values of ϵ_{r_1}. In addition, supporting numerical calculations are reported in Fig. 4*b*. The high gain response is also predicted for this lower frequency and the region for maximum radiated power at broadside.

Similar downward frequency shifts between measurements and simulations were previously reported by the authors for other SWL fed single-layer planar antenna structures [6, 7]. Such practical effects may be expected for other dielectric-based SWL-fed LWA designs when operating at microwave and millimetre-wave frequencies.

Conclusions: Presented is a low-cost and practical three-layer dielectric-based LWA structure for radiation at broadside. Antenna applications include microwave and millimetre-wave radar systems and compact, low-profile sensors for surveillance. Good agreement is observed between the simulated and measured beam patterns and gain values are greater than 11 dBi. A full-wave analysis was also developed to calculate the complex radial wavenumbers and radiated powers. Results support the observed antenna behaviour.

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One or more of the Figures in this Letter are available in colour online.

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