Compact dielectric impulse radiating antenna with a flat feed arm structure for low-frequency gain enhancement

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A compact dielectric impulse radiating antenna (IRA) with flat coplanar conical plate (CCP) feed arms was proposed for low-frequency gain enhancement. An empirical equation was proposed to predict the characteristic impedance of the CCP arms submerged in a dielectric half-space. The predicted value was used to determine the termination resistors that connect the feed arms to the reflector. Both the dielectric-filled and conventional air-filled IRAs were fabricated, and their performances were measured. The gain of the proposed dielectric-filled IRA is shown to be higher at frequencies lower than 3 GHz, where the diameter of the reflector is one wavelength.

Introduction: The impulse radiating antenna (IRA) was first introduced by C. E. Baum in 1989 [1]. The IRA consists of a paraboloidal reflector, a pair of transverse electromagnetic (TEM) feed arms, and termination resistors. When a step-like pulse is excited to the drive point of the feed arms, a spherical TEM wave propagates along the arms. The direct radiation from the arms in the broadside direction forms a prepulse, which has a shape similar to that of the input pulse. The spherical TEM wave propagating towards the reflector is converted into a locally plane wave in the aperture. The radiation from the aperture forms an impulse, which is a time-derivative of the input pulse. The spherical TEM wave along the arms is terminated at the end of the arms by the termination resistors.

Because of its impulse-radiating capability, IRA is suitable for many ultra-wideband (UWB) applications, such as electromagnetic pulse (EMP) simulators, remote sensing, and UWB communications [2–4]. For certain application platforms [5–7], a more compact IRA may be preferable. One approach is to use a flat IRA [8], whose arms are flush with the reflector rim. In this study, the size is further reduced by filling the flat IRA with a dielectric material as shown in Figure 1, which increases the electrical length of the impulse radiation mechanism.

Analytical solutions for the characteristic impedance of frequently used spherical TEM feed arms are available [9]. The value of the termination resistors in the IRA is set to match this characteristic impedance. However, these analytic solutions do not hold when the arms are partly submerged in the dielectric material. In this study, the characteristic impedance of the coplanar conical plates (CCPs) is investigated for use with the flat dielectric-filled IRA. A flat dielectric-filled IRA is subsequently designed and fabricated, and its performance is compared with that of the conventional flat air-filled IRA.

Flat CCP feed arms in a dielectric half-space: The characteristic impedance of the CCPs was investigated using a numerical model based on Ansys HFSS software. A pair of flat CCP arms with a finite length was submerged in a dielectric half-space with the arms flush with the air–dielectric boundary surface. The reflection coefficient was obtained in the frequency domain from the Ansys HFSS software and converted to the time-domain waveform. The reflection from the end of the arms was time-gated out, and the waveform was converted back to the frequency domain. The characteristic impedance of the CCPs was determined from the time-gated reflection coefficient, which is only associated with the outwardly travelling wave.

The model was validated through a series of experiments. A pair of 30-cm-long CCP arms was submerged in castor oil, as shown in Figure 2a. The permittivity of the castor oil was measured and included in the model. The characteristic impedance of the arms was determined from both the numerical model and the experiments with an arm angle α varying from 10° to 60° with 10° increments. The characteristic impedances obtained from the numerical model and the experiments are plotted in Figure 2b. The error between the numerical model and the simulation was less than 4.2%.

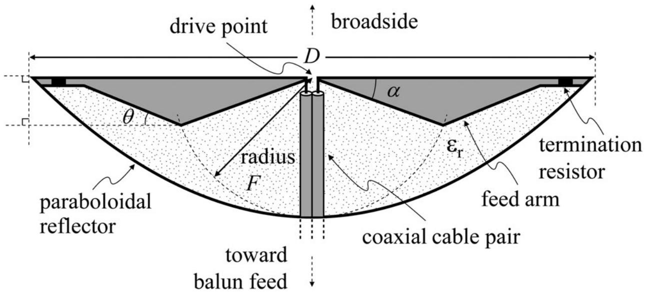

Fig. 1 *Illustration of the structure of a dielectric-filled IRA with flat feed arms. IRA, impulse radiating antenna.*

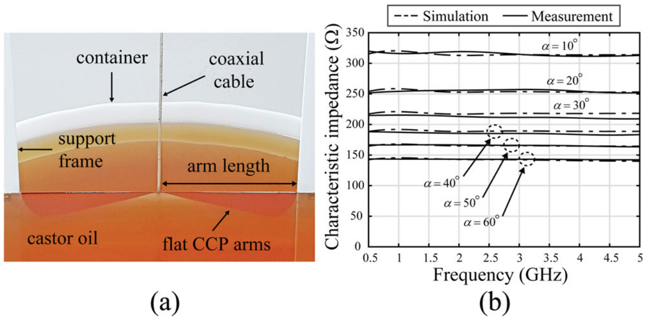

Fig. 2 *Measurement of the characteristic impedance for (a) flat CCP feed arms located at the boundary of castor oil and air, and (b) the resultant impedances with each α in comparison with the simulation results. CCP, coplanar conical plate.*

The characteristic impedance of the CCPs submerged in a dielectric half-space was investigated as a function of the permittivity and arm angle α. A simple empirical equation for the characteristic impedance Z_c of the flat CCPs was developed as follows:

$$Z_c \simeq \frac{\eta}{\sqrt[2.478]{\varepsilon_r}} \frac{K(m)}{K(1-m)}, \tag{1}$$

where η is intrinsic impedance and ε_r is the relative permittivity of the dielectric material. m is the elliptical modulus parameter and $K(m)$ denotes the complete elliptical integral of the first kind. Note that it is a slight modification from the expression for the conventional CCPs in a homogeneous space, which is analytically derived in [9].

The characteristic impedances for $10° < \alpha < 60°$ and $1 < \varepsilon_r < 10$ were determined from the empirical equation and plotted in a pseudo-colour graph in Figure 3. The characteristic impedance has a value between 100 and 450 Ω. The errors between the model and the empirical equation are denoted by the colour in scatter dots. The maximum error is seen to be less than 5%.

Flat IRA design and measurement: The structure of the proposed dielectric-filled IRA is shown in Figure 1. A paraboloidal reflector with an aperture diameter D of 10 cm and a focal length F of 2.5 cm was fabricated using 3D printing. The surface was coated with MG Chemicals 843AR conductive paint as shown in Figure 4a.

The interior of the reflector was filled with a dielectric material as shown in Figure 4b. The dielectric material was realized using a ceramic powder mixture with the formulation ratio of sintered Al_2O_3 powder 77.6 wt.%, castor oil 21.3 wt.%, and propylene glycol 1 wt.% [10]. The permittivity of the fabricated dielectric material was measured and plotted as shown in Figure 5. The permittivity is a function of frequency varying from 7 to 6 over the observed frequencies. A median value of 6.5 was used in the model for the characteristic impedance determination.

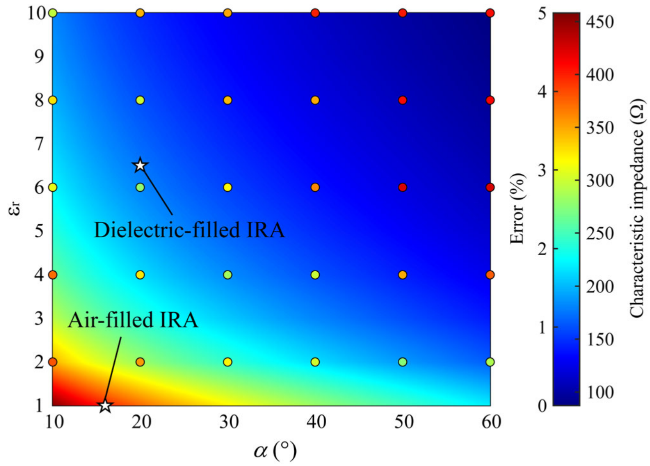

Fig. 3 *Characteristic impedance of the flat CCPs from the empirical equation, and the errors between the impedances from the simulation and the empirical equation in scatter dots. CCPs, coplanar conical plates.*

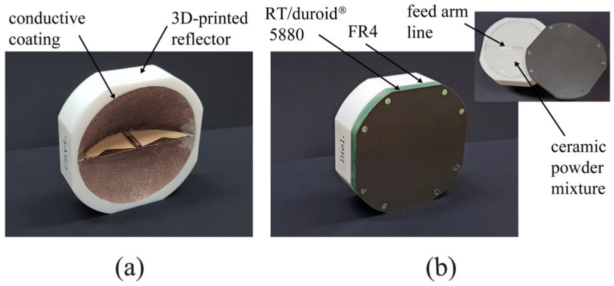

Fig. 4 *Photographs of the fabricated (a) air-filled and (b) dielectric-filled IRAs. IRA, impulse radiating antenna.*

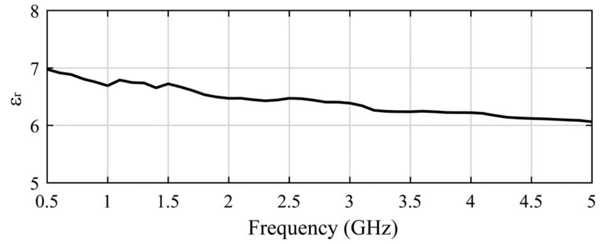

Fig. 5 *Relative permittivity of the fabricated composite material from the measurement.*

The angle of the arms was set to $\alpha = 20°$. Each arm was linearly tapered to the termination resistor with an angle $\theta = 36°$ starting at the radius of F. The arms were formed on a 0.25-mm-thick RT/duroid® 5880 substrate. The characteristic impedance of the fabricated arms corresponds to 175 Ω according to (1). The termination resistance value was determined to be 87.5 Ω considering a balanced arm, and Vishay 0603 thin-film resistors were used.

Two planar sheets of 8-mm-thick FR4 and 1.575-mm-thick RT/duroid® 5880 were attached to the aperture as a radome, which reduces the reflection of the plane wave at the medium boundary. A coaxial cable pair with a Hyperlabs HL9401 balun was used to drive the antenna [8]. To verify the performance of the dielectric-filled IRA, an air-filled IRA with the same reflector was fabricated with a characteristic impedance of 400 Ω, which is generally used for avoiding aperture blockage [11].

The reflection coefficients of the two fabricated antennas were measured and plotted in Figure 6, where the reference impedances were set to coincide with the feed arms characteristic impedance of the respective antennas. The reflection coefficients are less than −10 dB for both antennas, indicating that they can operate over UWB [12].

The gains of the two antennas were measured in an anechoic chamber and plotted in Figure 7. The gain of the proposed dielectric-filled IRA is shown to be higher at frequencies lower than 3 GHz, where the diameter

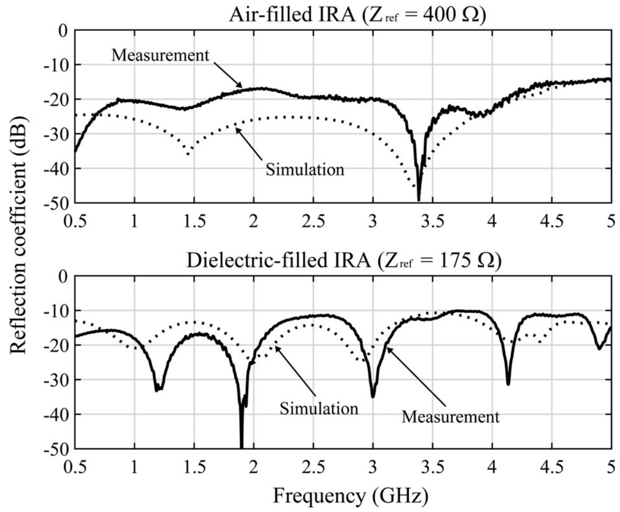

Fig. 6 *Measured reflection coefficients of the air-filled and dielectric-filled IRAs. IRA, impulse radiating antenna.*

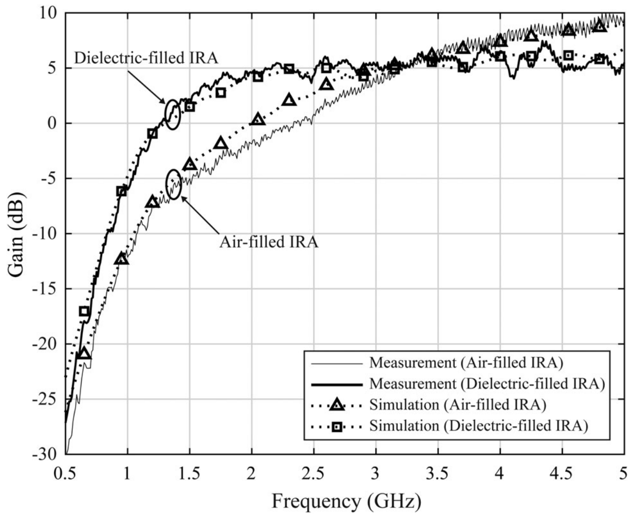

Fig. 7 *Measured absolute gains in the boresight direction for air-filled and dielectric-filled IRAs. IRA, impulse radiating antenna.*

of the reflector is one wavelength. The gain deviations of up to 7.5 dB are observed near 1.5 GHz. Thus, the proposed dielectric-filled IRA has an enhanced gain at low frequencies.

Conclusion: In this study, a compact flat IRA, whose reflector is filled with a dielectric material, is proposed to improve the low-frequency gain. An empirical equation for the characteristic impedance of the CCPs submerged in a dielectric half-space was developed as a function of permittivity and arm angle α. The empirical equation with the errors less than 5% over ultra-wide bandwidth can be used for flat IRA design. Both the proposed dielectric-filled and conventional air-filled IRAs were fabricated, and their performances were measured. The impedance bandwidths of both antennas are shown to be UWB through measurements. The gain of the proposed dielectric-filled IRA is higher at frequencies lower than 3 GHz and the gain improvement was achieved up to 7.5 dB near 1.5 GHz. The proposed IRA can be used in various UWB applications, including the electromagnetic characterization of pre-installed server rooms.

Author contributions: Lee, Junseop: Conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing – original draft

Kim, Kangwook: Conceptualization, funding acquisition, project administration, resources, supervision, writing – review & editing

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