Slot antenna excited by novel substrate integrated coaxial line cavity for millimetre wave application

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In this Letter, a novel compact slot antenna has been realised using substrate integrated coaxial line (SICL) cavity. SICL technology helps to achieve cavity size of $0.41\lambda_0 \times 0.48\lambda_0$ while maintaining its inherent advantage of self shielded and low loss transmission line at millimetre frequencies. A SICL cavity is designed by shorting the middle conductor at the two edges and keeping the other two edges separated from the sidewall. The eigenmode analysis affirms the presence of a dominant TEM mode at 28 GHz along with the presence of SICL even and odd modes. A half wavelength diagonal slot is etched on the bottom plate of the cavity to disturb the TEM mode surface current at 28 GHz. Measurement results show the SICL cavity backed slot antenna exhibits a gain of 5.6 dBi at 28.6 GHz and high front-to-back ratio better than 17 dB. The SICL-based cavity exhibits millimetre wave resonance with much smaller size, which helps to improve the compactness of the design. The proposed antenna can be used for millimetre wave applications like handheld mobile devices at millimetre-wave frequencies.

Introduction: Recent trends in communication systems have drawn the interest of industries and academics towards the millimetre wave frequencies, especially above 24 GHz because of its underlying advantages of low traffic and available broad bandwidth along with promising features, e.g. low latency and high data rates. Also, the path loss at 28 GHz band is low as compared to that at higher millimetre wave frequencies. Antennas designed at this frequency require low profile and small footprint for handheld mobile devices. Slot antennas are one such potential candidate. The radiations of the slot antenna are bidirectional in nature. However, the radiation can be made unidirectional by placing a reflector at quarter wavelength distance from the antenna, to have constructive interference of the forward and the reflected wave. A few literature have been reported in the past to design the substrate integrated coaxial line (SICL)-based slot antennas. A 45° linearly polarised slot antenna array [1], a homolaterally etched slot antenna array [2] has been proposed. SICL excited cavity backed patch antenna [3] and a 1×4 cavity backed patch antenna array have been proposed for Q-band applications [4], which use open cavity structure and degrades its shielded nature. In [5], SICL-based power divider has been used to excite the 2×4 C-shaped slots array to obtain high gain while maintaining a compact design. Few substrate integrated waveguide (SIW) cavity backed slot antennas have been reported in [6–8] designed at X-band and Ku band which occupy a comparatively larger footprint.

This Letter presents a novel SICL cavity backed slot antenna at millimeter wave frequency. According to the authors best knowledge, the proposed antenna is the first among the SICL cavity backed slot antennas which utilise SICL cavity modes to excite the antenna. The design provides a simple approach by cutting a slot on the bottom ground plate of the SICL cavity without disturbing the shielded nature of the feeding network. A GCPW to SICL transition is used to experimentally test the proposed antenna.

Design and principle of operation: SICL transmission line technology was first introduced by Gatti *et al.* [8]. The SICL transmission line consists of a middle conductor layer between the two conducting plates at the top and bottom of the two substrates. Bond layer is used as an adhesive to hold the two substrates together. Taconic TLY 5 substrate (permittivity $\epsilon_r = 2.2$, height 0.25 mm each) and Taconic FR-28 ($2.75 < \epsilon_r < 2.9$, height 0.1 mm) is the bonding material used to design the antenna using multilayer fabrication process. A plated through hole (PTH) via section is drilled across the length of the middle conducting strip to provide side wall shielding as obtained in a coaxial cable. A GCPW to SICL transition is used to excite TEM mode propagation in the SICL transmission line. A feeding via connects GCPW signal line to the middle layer of the SICL. SICL square cavity of sidewall approximately half wavelength ($\lambda_g/2$) is designed using (1) by shorting the two ends of the middle layer and keeping other two sidewalls at a distance of 0.2 mm from the middle plate.

$$L_c = \frac{c}{2 * f * \sqrt{\epsilon_r}} \tag{1}$$

where c represents speed of light in vaccum, f denotes the resonant frequency and ϵ_r denotes the permittivity of the substrate. The slot is made on the bottom plate of the SICL cavity and the GCPW feed line on the top plate of the SICL transmission line as shown in Fig. 1. The resonating mode has been identified from the eigenmode analysis in Ansofts HFSS. Two image planes AA' and BB' as shown in Fig. 2*a* are used as the reference plane to study the modes occurring at different frequencies. First four modes have been analysed and shown in Fig. 3. The plot for variation in the resonant frequency of the modes with varying length-to-width ratio (L_c/W_c) of the SICL cavity is depicted by the curve in Fig. 2*b*. The resonance obtained at 28 GHz is confirmed to be dominant TEM mode from the electric field distribution and surface current distribution as shown in Figs. 3*a* and *b*. However, the cavity exhibits resonances due to the dual nature of both SIW and SICL cavities. It is observed in the proposed cavity, even and odd modes exist along with the plane AA' and BB'. $TE^y_{110(\text{even})}$ mode having a sinusoidal distribution along with the BB′ is the conventional SIW mode and $TE^y_{110(\text{odd})}$ mode having a cosinusoidal distribution along with the BB′ is the higher-order SICL mode. Both the modes $TE^y_{110(\text{even})}$ and $TE^y_{110(\text{odd})}$ occur at approximately the same frequency. The fourth mode is TEM_2 which is the next higher-order TEM mode with two half wavelength variation along with the AA′. The electric field distribution and surface current distribution for the first four modes are shown in Fig. 4 for the proposed SICL cavity. For the proposed antenna, the length-to-width ratio (L_c/W_c) is 1 to improve out of band performance. However, to compensate the coupling resulting from the slot and the transmission line, the ratio of cavity length-to-width has been slightly tuned. For all the length-to-width ratio of the SICL cavity, the dominant mode remains TEM, as shown in Fig. 2*b*. A half wavelength ($\lambda_g/2$) diagonal slot is placed across the bottom conducting plate of the SICL cavity to perturb the surface current of the resonant mode.

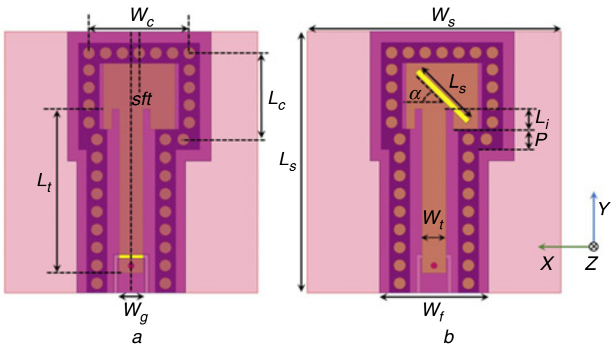

Fig. 1 *Design of the SICL cavity backed slot antenna*

a Top view
b Bottom view. The dimensions are (in mm): $W_c = 5.04$, $W_g = 1.36$, $L_c = 4.3$, $L_t = 8.2$, $P = 1$, $W_s = 12.7$, $W_f = 5.44$, $W_t = 1.2$, $L_s = 3.4$, $L_i = 1$, $\alpha = 45°$, $sft = 0.4$

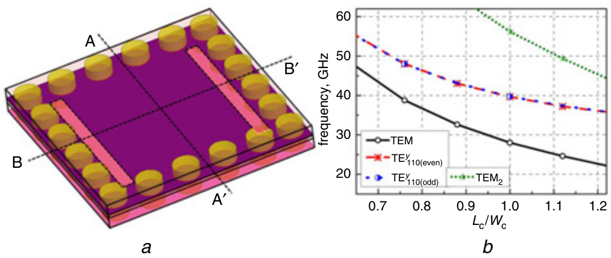

Fig. 2 *Mode chart of the SICL cavity*

a SICL cavity with the image plane AA′ and BB′
b Variation in resonant frequency of modes in SICL cavity with varying length to width ratio (L_c/W_c) of the SIC cavity

The length of the transmission line between the GCPW section and the SICL cavity is L_t. The width of the line W_t is tuned to provide the impedance matching between the SICL cavity backed slot antenna and the 50 Ω GCPW line. The length of the transmission line is kept at odd multiple of $\lambda_g/4$ to feed the slot loaded SICL cavity. A parametric analysis is stated in the next section to analyse the characteristics of the designed antenna.

Parametric analysis: SICL transmission line is inset in the SICL cavity to control the coupling and to set proper impedance matching. This is seen as the impedance matching degrades with varying lengths of the inset L_i in the middle plate of the SICL cavity as shown in Fig. 4*a*. The SICL transmission line feeding the SICL cavity is offset from the centre by *sft*. This controls the level of coupling between the SICL cavity and the transmission line as observed in Fig. 4*b*. The length of the radiating diagonal slot L_s is kept half wavelength at the resonating frequency. As shown in Fig. 4*c*, with an increment in the length of the slot, the resonant frequency shifts towards lower frequency. Also, the slot orientation is an important parameter that disturbs the surface current in the SICL cavity. A parametric study of the slot tilt (α) shows that $\alpha = 45°$ gives optimum coupling of the slot antenna with the SICL cavity mode as shown in Fig. 4*d* and as a result, it starts radiating into free space.

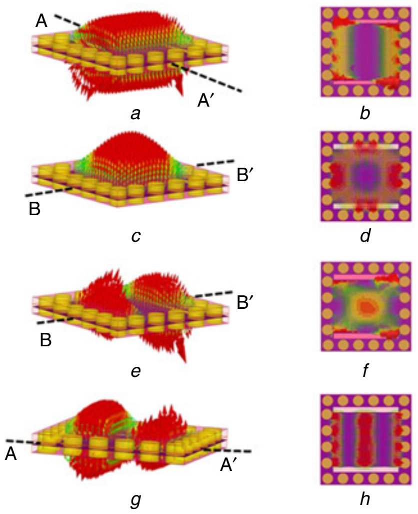

Fig. 3 *Vector electric field distribution in the SICL cavity in isometric view and vector surface current distribution in the bottom plane, respectively, for*
a, b TEM mode
c, d $TE^{y}_{110(even)}$ mode
e, f $TE^{y}_{110(odd)}$ mode, and
g, h TEM_2 (second harmonic) mode for the proposed SICL cavity

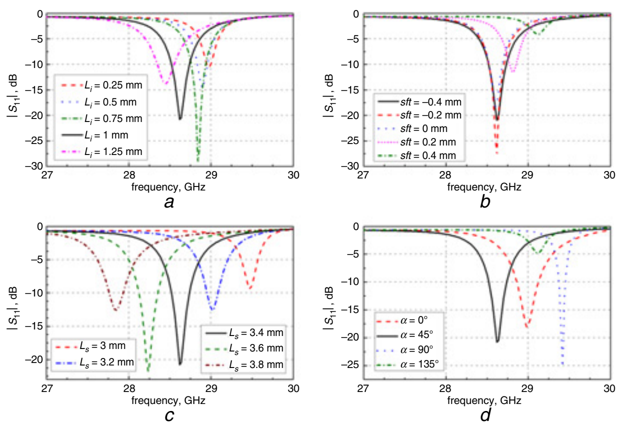

Fig. 4 *Parametric study of the proposed cavity for the design parameters, namely*
a Length of the inset cut (L_i) in the middle plate of the SICL cavity
b Feed offset (*sft*)
c Slot length (L_s)
d Slot orientation (α) of the proposed SICL cavity backed slot antenna

Simulated and measured results: The reflection coefficient for the simulated and fabricated design of the SICL cavity backed antenna is shown in Fig. 5*a* and the fabricated prototype of the SICL cavity backed slot antenna is in Fig. 5*b–c*. The simulated design and the measured antenna resonates at 28.6 GHz. The difference in reflection coefficient is accounted from the fabrication tolerance and limitation in the measurement setup of the proposed antenna. The electric field and surface current distribution of the proposed SICL cavity backed slot antenna are shown in Fig. 6. The electric field exists between middle to top and middle to bottom, which shows the TEM mode of propagation as observed in Fig. 6*c*. The simulated and measured gains of the antenna are 6 and 5.6 dBi, respectively. The deviation in the measured gain from the simulated gain is because of the 2.4 mm male to male adapter used to connect the VNA. The radiated pattern is measured in both *E*-plane ($\phi = 45°$) and *H*-plane ($\phi = 135°$) in accordance with the tilt in slot on the bottom plate. The measured and simulated radiation patterns are shown in Fig. 7. The proposed antenna exhibits maximum co-pol to cross-pol ratio of 28 dB with front-to-back ratio (FTBR) of 17.36 dB in the direction of maximum radiation. The size of the SICL cavity backed slot antenna is found to be compact in compared with other technologies based design including SIW cavity backed antennas proposed earlier.

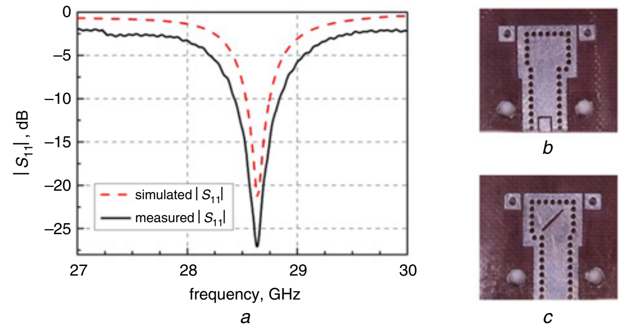

Fig. 5 *Experimental validation*
a Simulated and measured reflection coefficient of the proposed SICL cavity backed slot antenna. Fabricated design in
b Top view, and
c Bottom view

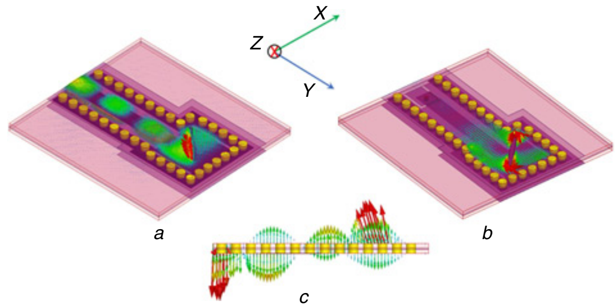

Fig. 6 *Field distribution and surface current*
a Electric field distribution in the isometric view
b Surface current in the isometric view
c Electric field in side view of the proposed SICL cavity backed slot antenna

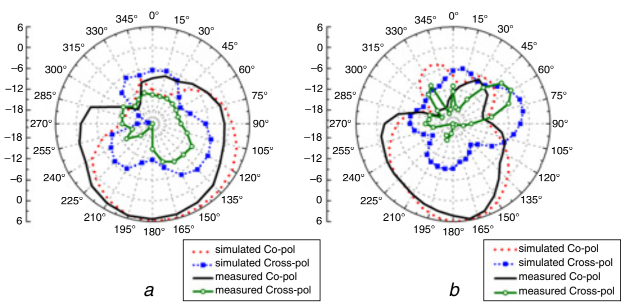

Fig. 7 *Radiation pattern of the proposed antenna*
a E-plane
b H-plane at 28.36 GHz

Conclusion: SICL cavity backed slot antenna has been proposed to operate at millimetre wave frequency. The shielded nature of the SICL makes it highly useful for designing cavity backed antennas. The novelty of this work is the excitation of the slot antenna by SICL cavity in a much smaller footprint. These modes have been studied in this Letter and dominant TEM mode has been used to excite the proposed antenna. The proposed antenna exhibits FTBR of 17.36 dB and co-pol to cross-pol ratio of 28 dB with the measured gain of 5.6 dBi. This antenna can be used for millimetre wave application like mobile handheld devices, other 5G user equipments and further be used as the basic element for implementing antenna array for future 5G applications.

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

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