A Novel Substrate Integrated Suspended Line Wideband Leaky-Wave Antenna

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***Abstract*—A novel compact wideband leaky-wave antenna based on substrate integrated suspended line is proposed. The proposed antenna is designed to be self-packaged format with five substrate layers and embedded air cavities. Asymmetric feeding is utilized to excite the first higher order mode. In order to achieve the suppression of backlobe and impedance matching, the tapered radiator with an etched slot is introduced. According to the measured results, the maximum antenna gain of 15.1 dBi and 50% fractional bandwidth from 7.5 to 12.5 GHz are obtained. Additionally, the self-packaged antenna has good radiation properties with low backlobe and sidelobe. The scanning angle of the measured main beam is about 44° ranging from 10° to 54°.**

***Index Terms*—Asymmetric feeding, leaky-wave antenna, substrate integrated suspended line (SISL), tapered.**

I. Introduction

Leaky-wave antennas, which are categorized as traveling-wave antenna type, have received much attention in recent years due to space-scanning capability and high gain. Several kinds of leaky-wave antennas have been proposed [1]–[3]. A short leaky-wave antenna with length of $1.14\lambda_0$ and backlobe of -7.5 dB is proposed in [4]. The impedance bandwidth achieves about 1.30 GHz for 7 dB return loss, and the maximum gain is 6.5 dBi. A composite right/left-handed leaky-wave antenna based on substrate integrated waveguide (SIW) supporting continuous beam scanning from backward to forward direction is proposed in [5]. The measured maximum gain of 12 dBi and 43% fractional impedance bandwidth are obtained. An SIW leaky-wave antenna with uniform transverse slots is proposed in [6], which has a maximum gain of 9 dBi at the expense of relative high sidelobe level. The leaky-wave butterfly-like SIW antenna with eight wings is proposed to improve antenna gain to 10 dBi [7]. Nevertheless, the sidelobe level is relatively high below 10.5 GHz.

In this letter, a novel substrate integrated suspended line (SISL) leaky-wave antenna is presented to obtain low sidelobe levels and relatively high gain based on the proposed SISL technology in [8]. The proposed antenna, which is composed of five substrate layers and fabricated by printed circuit board (PCB) technology, is designed to be self-packaged, and thus the bulky and expensive mechanical housing is avoided. A tapered radiator is designed to reduce the backlobe and improve the impedance matching. In order to further reduce the backlobe, a rectangular slot is embedded in the tapered radiator. Both the measurement and simulation results show that the proposed antenna has a fractional bandwidth of 50%, low sidelobe level smaller than -15 dB, and low cross-polarization level lower than -20 dB. The main beam scans from 10° to 54° and the maximum antenna gain is 15.1 dBi.

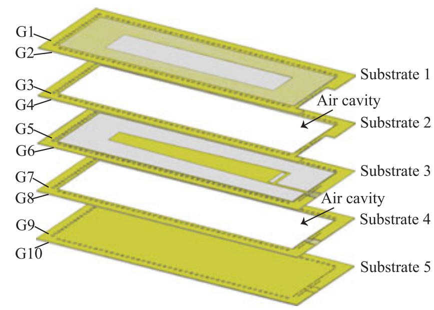

Fig. 1. Stack up configuration of the entire antenna.

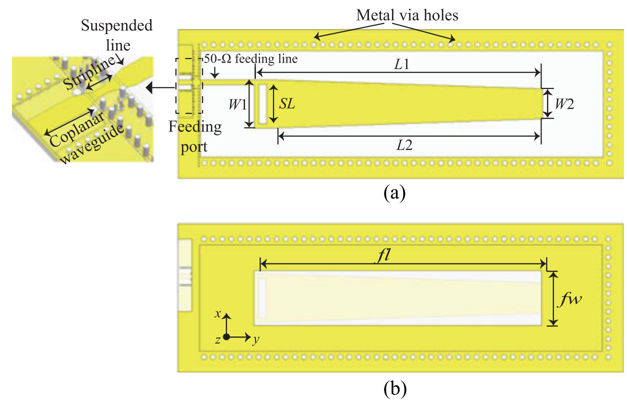

Fig. 2. Configuration and parameters of the proposed antenna. (a) Radiator on G5. (b) Rectangular slot on G2.

II. Antenna Design

The configuration of the proposed antenna is shown in Figs. 1 and 2. As shown in Fig. 1, the antenna contains five substrate layers successively named substrate 1, substrate 2, substrate 3, substrate 4, and substrate 5 from the top to bottom. In the design, substrates 1, 2, 4, and 5 are FR-4 laminates with

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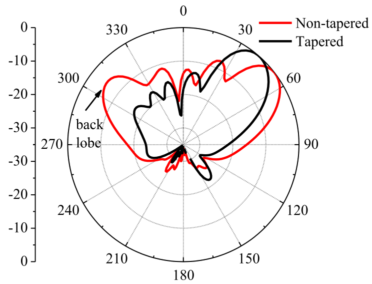

Fig. 3. Simulated normalized radiation patterns of the nontapered (or uniform width) and tapered antenna at 10 GHz.

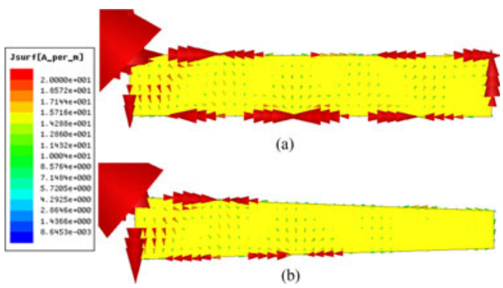

Fig. 4. Simulated surface current distributions at 10 GHz. (a) Nontapered (or uniform width) SISL leaky-wave antenna. (b) Tapered SLSL leaky-wave antenna.

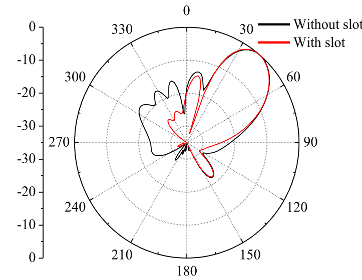

Fig. 5. Simulated normalized radiation patterns of the antennas without slot and with slot at 10 GHz.

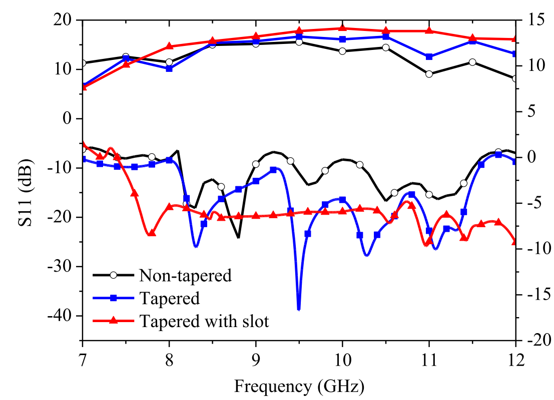

Fig. 6. Simulated reflection coefficients and gains of the nontapered (or uniform width) antenna, tapered antenna, and tapered antenna with slot.

thickness $h_1 = 20$ mil, $\varepsilon_{r1} = 4.4$, and $\tan\delta = 0.02$, and substrate 3 is Rogers 4003C laminate with thickness $h_2 = 8\,\text{mil}$, $\varepsilon_{r2} = 3.38$, and $\tan\delta = 0.0027$. Plated metal is on both sides of each substrate as standard PCB, and ten metal layers are named as G1–G10 shown in Fig. 1. Two rectangular apertures with the same dimensions and locations are cut on substrate 2 and substrate 4, respectively, to form two air cavities. The metal layers around the edge of substrates are connected through metalized via holes. Fig. 2(a) illustrates the structure and parameters of tapered radiator. Asymmetric feeding is utilized to excite the first higher order mode. The total length *L*1 of the tapered radiator is chosen to be $3.2\lambda_0$ at 10 GHz. A large rectangular etched slot on G2 is plotted in Fig. 2(b), which has a significant effect on the performance of the proposed antenna.

Fig. 2(a) shows the configuration and parameters of the proposed SISL leaky-wave antenna. In order to test, the transition structure is proposed in the feeding port. The transition contains three parts: suspended line, stripline, and coplanar waveguide, and the impedance of each part is designed to be 50 Ω. More descriptions in detail about the transition are introduced in [9]. To radiate 90% of the power, the length of conventional leaky-wave antenna in [10] needs to be $4.85\lambda_0$. For the proposed design in this letter, the length of three wavelengths and width of half wavelength can be achieved. Numerical methods [11]–[13] were proposed to obtain the radiation characteristics of the leaky-wave antenna, and for our design, the full-wave electromagnetic simulation software HFSS 15 is used for the following investigation and design.

Fig. 3 shows the normalized radiation patterns in H-plane of nontapered (or uniform width) antenna and tapered antenna at 10 GHz. Both the nontapered and tapered antenna are based on SISL technology, which have the same three-dimensional structure with the antenna shown in Fig. 1, while the only difference is whether the radiator is tapered or not as shown in Fig. 4. It is observed that for nontapered antenna, undesired high backlobe occurs. When the radiator is tapered, the magnitude of backlobe is reduced dramatically. Fig. 4 plots the simulated surface current distributions of nontapered antenna and tapered antenna at 10 GHz. It can be seen that there exists strong surface current at the end of the nontapered leaky-wave antenna, which results in the serious backlobe. On the contrary, the surface current at the end of the tapered antenna is weak, which means that the remaining power reflecting from the end of antenna radiator is little, and then the backlobe is reduced.

In order to further suppress the backlobe, a rectangular slot is etched on the radiator shown in Fig. 2(a). Fig. 5 demonstrates the radiation patterns in an H-plane at 10 GHz of the leaky-wave antenna with slot and without slot. As seen from Fig. 5, the magnitude of back lobe with slot is smaller than that without slot because the slot changes the surface current distributions and makes the surface current weaker at the end of the antenna. Fig. 6 shows the reflection coefficients and gains of the three antennas aforementioned. It can be seen that the tapered structure and the slot can improve the impedance matching. For the tapered antenna with slot, the lowest operating frequency is reduced to 7.5 GHz and the overall impedance matching is better, which is because after the slot is embedded, the real part of the impedance is changed to almost 50 Ω, and the imaginary part of the impedance is almost 0 Ω. The antenna gain can be improved due to the backlobe suppression when the radiator is tapered with slot. The final simulated maximum gain of the tapered antenna with slot is 14.1 dB.

Additionally, the width *fw* of the large rectangular etched slot [see Fig. 2(b)] affects the performance of the proposed antenna. Fig. 7 depicts the radiation patterns in H-plane of different widths at 10 GHz. The radiation angle of main lobe gradually inclines to the broadside (*z*) direction, and the beamwidth be-

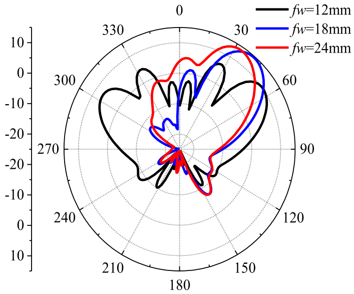

Fig. 7. Simulated radiation patterns of the proposed SISL leaky-wave antenna with different width *fw* at 10 GHz.

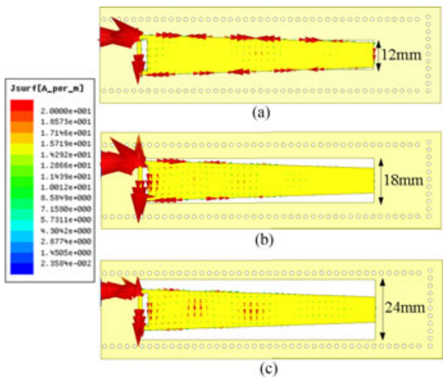

Fig. 8. Simulated surface current distributions of the proposed SISL leaky-wave antenna with different width *fw* at 10 GHz. (a) $fw = 12$ mm. (b) $fw = 18$ mm, (c) $fw = 24$ mm.

comes larger with increasing of the width *fw*. However, when the width *fw* is less than the width *W* of the radiator, the magnitude of the backlobe is larger while the magnitude of main lobe is smaller. Since the surface current and electric field are transverse, the transverse width *fw* influences the effective electrical width, and then impacts the performance of the antenna. When the rectangular slot width *fw* is smaller than the antenna width, the antenna operates as a nontapered leaky-wave antenna similar with that shown in Fig. 4(a). From Fig. 8, we can see that the surface current at the end of radiator is very strong when the width $fw = 12$ mm, which results in high backlobe. Therefore, $fw = 18$ mm is chosen according to above analysis and optimization.

In addition, some physical dimensions such as *W*1, *L*1, and *SL* have significant effects on the performance of the antenna. The final dimensions are specified as follows: $L1 = 95$ mm, $L2 = 90$ mm, $W1 = 16$ mm, $W2 = 10$ mm, $SL = 13$ mm, $fl = 95$ mm, and $fw = 18$ mm.

III. Simulated and Measured Results

The proposed antenna was fabricated, and the photographs are shown in Fig. 9. The simulated and measured reflection coefficients of the proposed SISL tapered leaky-wave antenna with slot are shown in Fig. 10. A good agreement between the simulated and measured results is achieved. The frequency shifting about 0.3 GHz is observed. This disagreement is reasonable and may be due to the fabrication tolerance of the antenna. The simulated impedance bandwidth defined by $S_{11} < -10$ dB is from 7.2 to 12.5 GHz, and the measured impedance bandwidth is from 7.5 to 12.5 GHz with 50% fractional bandwidth.

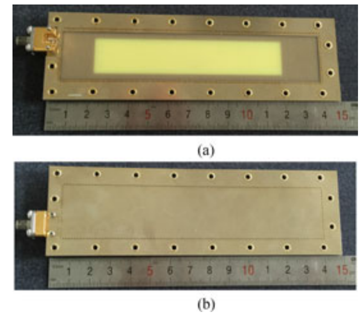

Fig. 9. Photographs of the fabricated antenna. (a) Top view. (b) Bottom view.

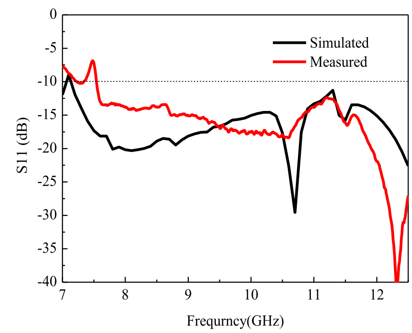

Fig. 10. Simulated and measured reflection coefficient of the proposed SISL leaky-wave antenna.

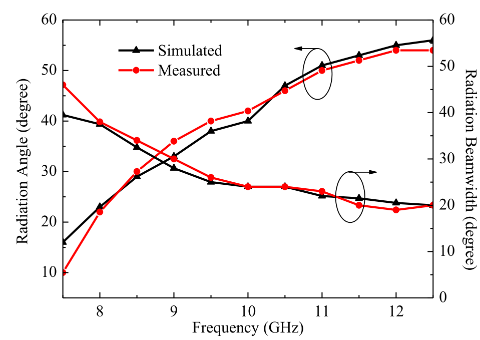

Fig. 11. Simulated and measured radiation angle θ_m and beamwidth $\Delta\theta$ of the SISL leaky-wave antenna.

Fig. 11 compares the simulated and measured θ_m and $\Delta\theta$ of the SISL leaky-wave antenna. It can be seen that the simulated and measured results have a good agreement. The simulated radiation angles are from 16° to 56°, and measured results are from 10° to 54° across the bandwidth from 7.5 to 12.5 GHz. The simulated 3 dB radiation beamwidth, $\Delta\theta$, ranges from 39.5° to 20° and measured result ranges from 46° to 19° in the passband from 7.5 to 12.5 GHz. Fig. 12 illustrates the co- and cross-polarization radiation patterns in H-plane of the proposed antenna at 8, 9, 10, and 11 GHz. As shown, the proposed antenna has low cross-polarization level, which is lower than -20 dB. Very good consistency between the measured and simulated copolarization radiation patterns could be observed. The sidelobe level of the measured radiation pattern is smaller than -15 dB. The main beam direction of the proposed antenna shifts from the broadside (z) direction to end fire direction with frequency increasing. Specifically, the main beam direction is 22°, 36°, 42°, 50° at 8, 9, 10, and 11 GHz, respectively. The gain, directivity, and radiation efficiency are shown in Fig. 13.

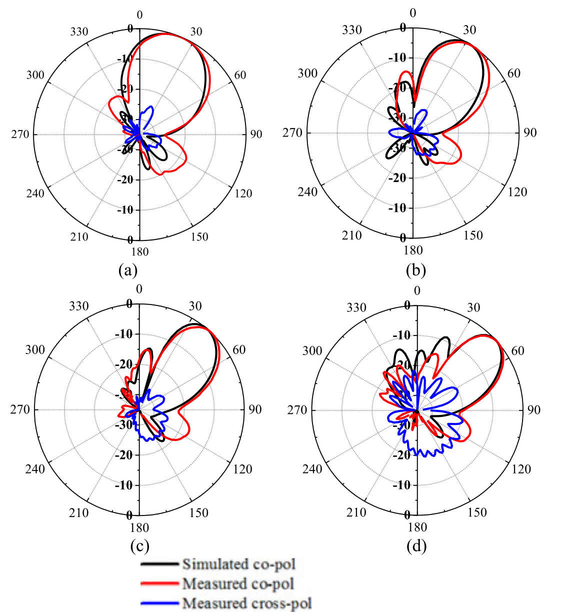

Fig. 12. Normalized simulated and measured radiation patterns in H-plane (*yoz*-plane) at different frequencies: (a) 8, (b) 9, (c) 10, and (d) 11 GHz.

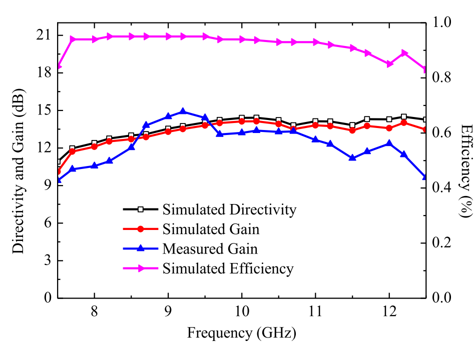

Fig. 13. Gain, directivity, and radiation efficiency of the proposed SISL leaky-wave antenna.

TABLE I
PERFORMANCE COMPARISONS BETWEEN THE PROPOSED ANTENNA AND REFERENCED ANTENNAS

Antennas	L (λ_0)	Fractional Bandwidth[a]	Bandwidth[a] (GHz)	Maximum Gain (dB)
[4]	1.3	33%	3.3–4.6	6.5
[5]	6.5	43.5%	9.0–14.0	12
[7]	6	22%	10–12.5	11
This work	3.2	50%	7.5–12.5	15.1

[a]The fractional bandwidth of 33% and bandwidth from 3.3 to 4.6 GHz are defined by the 7 dB return loss.

The measured gain is close to the simulated gain. Measured results demonstrate that the proposed antenna has high gains ranging from 10.2 to 15.1 dB in the band from 7.7 to 12.4 GHz. The simulated gain is close to the simulated directivity, and the simulated radiation efficiency is better than 90%. Table I summarizes the performances of the proposed SISL leaky-wave antenna and other referenced leaky-wave antennas. L is the main length of the antennas, and λ_0 is the free-space wavelength at the center operating frequency. It can be seen that the proposed antenna has higher gain and wider bandwidth compared with above mentioned antennas.

IV. CONCLUSION

In this letter, a novel SISL leaky-wave tapered antenna with slot has been presented. The asymmetric-feeding for first higher order mode excitation, tapered radiator with slot for backlobe suppression, and impedance matching is introduced. The proposed antenna, fabricated by low-cost PCB technology, obtained excellent performance: The measured backlobe and sidelobe levels are less than -15 dB, and the measured scanning angle covers 44°, i.e., from 10° to 54°. The maximum gain of 15.1 dB in the 50% fractional bandwidth is achieved. The designed antenna, which demonstrated advantages of self-packaging, high antenna gain, and compact size, is attractive for X-band applications.

REFERENCES

[1] A. A. Oliner and D. R. Jackson, "Leaky-wave antennas," in *Antenna Engineering Handbook*, J. L. Volakis, ed. New York, NY, USA: McGraw-Hill, 2007, ch. 11.
[2] C. Caloz, D. R. Jackson, and T. Itoh, "Leaky-wave antennas," in *Frontiers in Antennas: Next Generation Design & Engineering*. New York, NY, USA: McGraw-Hill, Dec. 2011, ch. 9.
[3] D. R. Jackson, C. Caloz, and T. Itoh, "Leaky-wave antennas," *Proc. IEEE*, vol. 100, no. 7, pp. 2194–2206, Jul. 2012.
[4] J.-W. Wu, C. F. Jou, and C.-J. Wang, "A compact wideband leaky-wave antenna with etched slot elements and tapered structure," *IEEE Trans. Antennas Propag.*, vol. 58, no. 7, pp. 2176–2183, Jul. 2010.
[5] Y.-L. Lyu, X.-X. Liu, and P.-Y. Wang, "Leaky-wave antennas based on noncutoff substrate integrated waveguide supporting beam scanning from backward to forward," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2155–2164, Jun. 2016.
[6] J. Liu, D. R. Jackson, and Y. Long, "Substrate integrated waveguide (SIW) leaky-wave antenna with transverse slots," *IEEE Trans. Antennas Propag.*, vol. 60, no. 1, pp. 20–29, Jan. 2012.
[7] Y. Mohtashami and J. Rashed-Mohassel, "A butterfly substrate integrated waveguide leaky-wave antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3384–3388, Jun. 2014.
[8] K. Ma and K. T. Chan, "Quasi-planar circuits with air cavities," PCT Patent WO/2007/149046, 2007.
[9] L. Li, K. Ma, N. Yan, Y. Wang, and S. Mou, "A novel transition from substrate integrated suspended line to conductor backed CPW," *IEEE Microw. Wireless Compon. Lett.*, vol. 26, no. 6, pp. 389–391, Jun. 2016.
[10] Y.-L. Chiou, J.-W, Wu, J.-H. Huang, and C. F. Jou, "Design of short microstrip leaky-wave antenna with suppressed back lobe and increased frequency scanning region," *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 3329–3333, Oct. 2009.
[11] J. L. Gómez-Tornero, A. J. Martínez-Ros, and R. Verdú-Monedero, "FFT synthesis of radiation patterns with wide nulls using tapered leaky-wave antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 518–521, 2010.
[12] J. L. Gómez-Tornero, A. T. Martínez, D. C. Rebenaque, M. Gugliemi, and A. Álvarez-Melcón, "Design of tapered leaky-wave antennas in hybrid waveguide-planar technology for millimeter waveband applications," *IEEE Trans. Antennas Propag.*, vol. 53, no. 8, pp. 2563–2577, Aug. 2005.
[13] P. Lampariello, F. Frezza, H. Shigesawa, M. Tsuji, and A. A. Oliner, "A versatile leaky-wave antenna based on stub-loaded rectangular waveguide: Part I—Theory," *IEEE Trans. Antennas Propag.*, vol. 46, no. 7, pp. 1032–1041, Jul. 1998.