A 79-GHz Resonant Laminated Waveguide Slotted Array Antenna Using Novel Shaped Slots in LTCC

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***Abstract*—This letter presents a laminated waveguide (LWG)-based slotted array antenna in LTCC. The introduced novel slot shape derived from a standard longitudinal offset slot provides a further degree of freedom for the antenna design by bending the outer sections of the slot. Based on the characteristics of a single slot, the design procedure of an antenna array with amplitude tapering at a constant slot offset is presented. As an example, design, realization, and measurement of a 12-element array at 79 GHz with Dolph–Chebyshev power distribution with a sidelobe level of −20 dB are presented.**

***Index Terms*—Low temperature co-fired ceramic (LTCC), millimeter-wave antenna arrays, slotted waveguide antenna arrays, substrate integrated waveguide (SIW).**

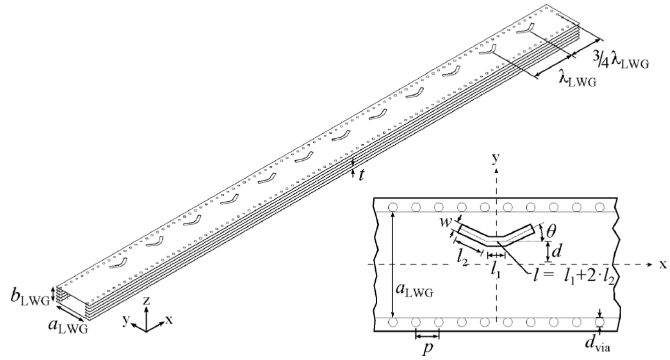

Fig. 1. Configuration and slot geometry of the proposed 79-GHz LWG 12-slot array antenna in LTCC.

I. Introduction

SLOTTED waveguide antenna arrays have always played an important role in navigation, radar, and other high-frequency systems. They exhibit low loss and radiate linear polarization with a low level of cross polarization. However, their complex fabrication at millimeter-wave frequencies has so far prevented their use in cost-sensitive commercial applications such as automotive radar. With the development of substrate integrated waveguides (SIWs) [1], also known as laminated waveguides (LWGs) [2], waveguide-like structures can be synthesized using via rows embedded in a dielectric substrate with top and bottom metallization. Therefore, completely planar designs of slotted waveguide arrays can be realized [3], [4], offering the same planar interconnectivity as standard microstrip antennas. In [5] and [6], the feasibility of SIW-based slot antennas at 76/79 GHz on relatively low-permittivity materials has been presented. A single-slot W-band antenna and small arrays in a photoimageable thick-film technology are reported in [7] and [8], respectively. In this letter, we present the design of a 79-GHz antenna array in high-permittivity low temperature co-fired ceramic (LTCC) intended to be used in future short-range radar (SRR) applications [9]. Using standard longitudinal slots for an array design results in very small offsets that are prone to even small manufacturing tolerances. An alternative could be to use inclined slots where the slots are rotated around the waveguide axis to adjust their individual coupling. Although small offsets correspond to rather moderate inclination angles, this antenna type was not taken into consideration due to its potentially higher cross-polarization level. Furthermore, transverse slots cannot be used either since the slot length for a low coupling slot would extend beyond the width of the waveguide. Therefore, a novel slot shape is introduced, allowing a low-sidelobe-level antenna design at a relatively large constant slot offset and maintaining low cross-polarization level at the same time.

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II. Design of the LWG Slotted Array Antenna

In general, antenna design at millimeter-wave frequencies on LTCC material requires high accuracy regarding metallization geometry and via placement. Therefore, the antenna is realized on a loss-optimized TDK LTCC material system offering the possibility of a high-precision fine-line photo-imaging process on the outer metallization layers [10]. The dielectric properties at 79 GHz determined by a quasi-optical measurement are $\epsilon_r = 7.28$ and $\tan\delta = 0.006$. Therefore, the dimensions of an LWG are scaled with a factor of $1/\sqrt{\epsilon_r} = 0.37$ compared to a standard WR-12 waveguide, i.e., $a_{\rm LWG} = 1.15$ mm, $b_{\rm LWG} = 0.59$ mm (five layers of LTCC, sintered layer thickness $t = 0.118$ mm). The slot lengths, however, are only scaled with an estimated factor of $\sqrt{2/(\epsilon_r+1)} = 0.49$ due to the effective permittivity at the dielectric–air interface. According to the relatively short guided wavelength $\lambda_{\rm LWG} = 1.73$ mm $= 0.456\lambda_0$ (with λ_0 as free- space wavelength at 79 GHz), slots can be placed only on one side from the center line (cf. Fig. 1) without generating unwanted grating lobes. Moreover, a too-close spacing, and therefore increased coupling of the slots, is avoided. The slot width is set to $w = 0.1$ mm, via diameter is $d_{\rm via} = 0.1$ mm, and

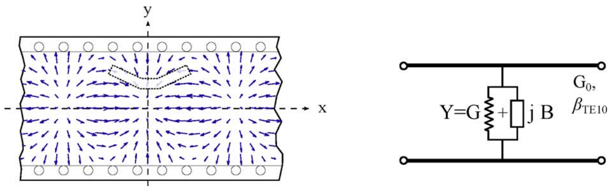


Fig. 2. Surface current distribution and equivalent network representation.

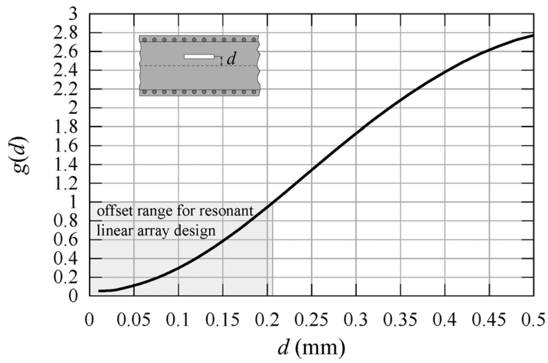


Fig. 3. Normalized resonant conductance at 79 GHz versus offset for a standard longitudinal slot ($\theta = 0°$).

via pitch $p = 0.25$ mm. The antenna array is terminated with a short circuit at a distance of three-quarter guided wavelengths from the center of the last radiating slot. The detailed design procedure based on the analysis of a single slot is described in the following.

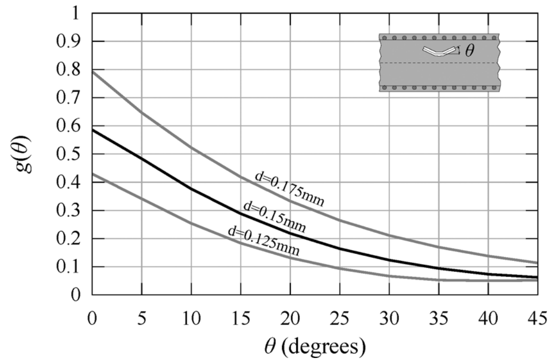


Fig. 4. Normalized resonant conductance versus bending angle at different offsets.

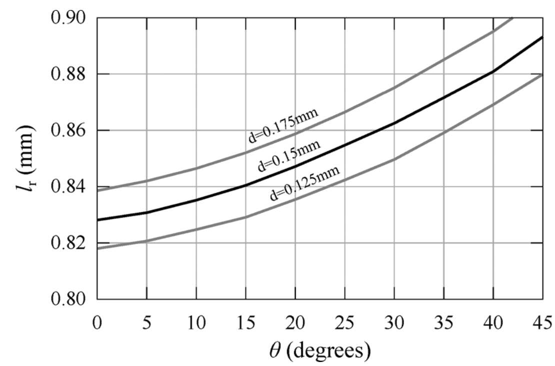


Fig. 5. Resonant length versus bending angle.

A. Single-Slot Characteristics and Equivalent Model

Resonant slotted array antennas can be efficiently designed by a technique developed by Elliot [11], [12] analyzing the scattering properties of a single slot with respect to length and offset. Near resonance, a displaced slot from the center line can be modeled as a shunt admittance since it predominantly interrupts the transverse currents (y-direction) in the top metallization. If the outer sections ($l_2 = 0.4 \cdot l$) of a slot are bent by an angle θ as depicted in Fig. 1, the shunt admittance model is still valid since the longitudinal current components (x-direction) interrupted by the outer slot sections have opposite direction (cf. Fig. 2). The same applies for radiation polarized in the x-direction, which is also canceled, assuring a low cross polarization. In line with Stegen's factorization for longitudinal slots [13], the equivalent shunt admittance for a bent offset slot can be formulated as follows:

$$\frac{Y(d,\theta,l,f)}{G_0} = \frac{G_{\rm r}(d,\theta)}{G_0} \cdot \frac{G+jB}{G_{\rm r}} = g(d,\theta) \cdot h(k) = g(d,\theta) \cdot [h_1(k) + jh_2(k)] \quad (1)$$

where $Y(d,\theta,l,f)$ is the admittance of the slot within a waveguide of characteristic conductance G_0; d, θ, and l are the offset, bending angle, and length of the slot; $g(d,\theta) = (G_{\rm r}(d,\theta)/G_0)$ is the normalized resonant conductance; $k = (l/l_{\rm r}(d,\theta))$ is the ratio of slot length to resonant slot length, and $h(k) = h_1(k) + jh_2(k)$ is the ratio of slot admittance to resonant conductance. The following figures illustrating these quantities are extracted from a full-wave finite-difference time-domain (FDTD) simulation of an isolated slot at $f = 79$ GHz as presented in [14]. Let us first consider the normalized resonant conductance g of a standard unbent slot ($\theta = 0°$) as a function of slot offset d as shown in Fig. 3. It can be seen that, at the given LWG dimensions, the suitable slot offsets for resonant linear array designs, i.e., $g < 1$, are limited to the range $0 \ldots 0.21$ mm. Hence, longer arrays using amplitude tapering result in very small offsets that are susceptible even to a small layer misalignment during the manufacturing process. Therefore, the normalized resonant conductance is investigated as a function of bending angle θ at different offsets (Fig. 4) with the corresponding resonant slot lengths given in Fig. 5. It is found that a wide range of resonant conductance values can also be covered using bent slots without adjusting the offset. The functions $h_1(k)$ and $h_2(k)$ are exemplary shown for various bending angles at an offset of $d = 0.15$ mm in Figs. 6 and 7, respectively. For large angles, both curves show significant deviation from the behavior of an unbent slot. Hence, it is necessary to compute $h(k)$ for each bending angle appearing during the design process of an array.

Finally, Fig. 8 shows the normalized radiated power $p_{\rm rad} = 1 - ((1-g)/(1+g))^2$ of a slot that is used to adjust the desired amplitude distribution within an array.

B. Array Design

The single-slot characteristics presented above are used to design a 12-element slotted array antenna applying a Dolph–Chebyshev amplitude distribution with -20 dB sidelobe level (SLL). Since the slots, and therefore the equivalent shunt admittances in a resonant linear waveguide array, are

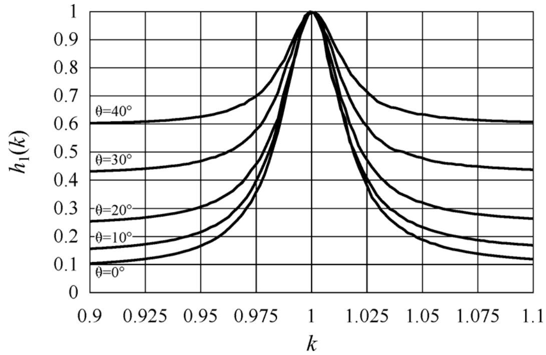


Fig. 6. G/G_{r} vs. $k = l/l_{\mathrm{r}}$ for a bent longitudinal slot with offset $d = 0.15$ mm.

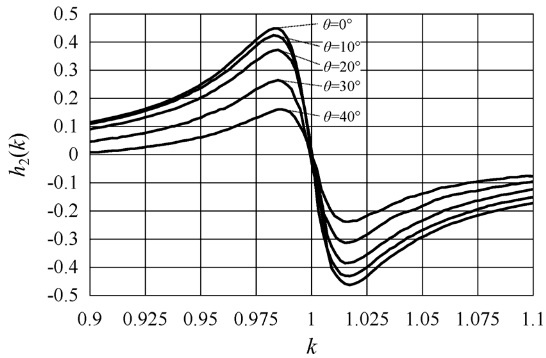


Fig. 7. B/G_{r} versus $k = l/l_{\mathrm{r}}$ for a bent longitudinal slot with offset $d = 0.15$ mm.

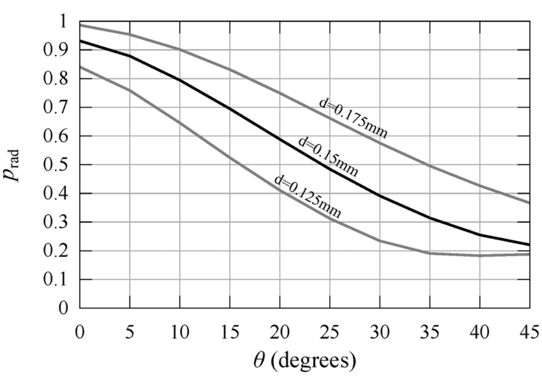


Fig. 8. Normalized radiated power of a single slot.

connected in parallel, the initial values for the array design have to fulfill the matching condition

$$g_{\mathrm{tot}} = \sum_{n=1}^{12} g_n = 1. \tag{2}$$

At the same time, the chosen slots have to comply with the desired amplitude distribution. An iterative approach to find a valid set of initial slot parameters is as follows: A slot is arbitrarily chosen along the curve in Fig. 8. It defines the maximum normalized amplitude coefficient within the array referred to as $g_{\max}$. The remaining slots are positioned along the curve according to the desired amplitude distribution. If the corresponding g-values result in $g_{\mathrm{tot}} < 1$, $g_{\max}$ has to be increased or decreased in the case of $g_{\mathrm{tot}} > 1$. Although the initial values

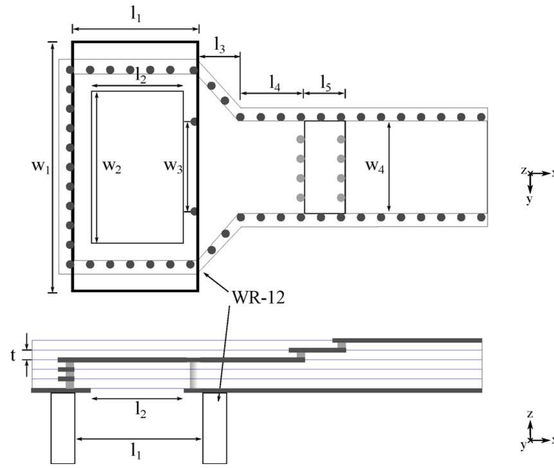
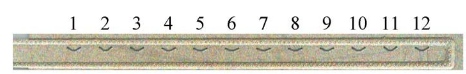


Fig. 9. Top and cross-section views of broadband WR-12-to-LWG transition. Design parameters: $w_1 = 3.1$ mm, $w_2 = 1.89$ mm, $w_3 = 1.23$ mm, $w_4 = 1.15$ mm, $l_1 = 1.55$ mm, $l_2 = 1.14$ mm, $l_3 = 0.56$ mm, $l_4 = 0.8$ mm, $l_5 = 0.5$ mm, $t = 0.118$ mm.

TABLE I
SLOT BENDING ANGLES AND LENGTHS OF THE PROPOSED 12-SLOT ANTENNA ARRAY



Slot No. n	Amplitude weight	θ (degrees)	l (mm)
1	0.731	31	0.847
2	0.553	37	0.856
3	0.709	31	0.847
4	0.845	27	0.841
5	0.946	24	0.837
6	1	23	0.836
7	1	23	0.836
8	0.946	24	0.837
9	0.845	27	0.841
10	0.709	31	0.847
11	0.553	37	0.856
12	0.731	31	0.847

result in a satisfactory radiation performance, the matching can be further optimized. Therefore, the mutual coupling between directly adjacent slots is also taken into account. The coupling can be expressed as a mutual admittance term. This is calculated from the admittance obtained from the simulation of two slots spaced λ_{LWG} from each other minus their isolated admittance values. Following this, the slots are adjusted accordingly in angle and length to compensate for their mutual coupling admittance using the functions g and $h(k)$ presented above. The sets of slots are iteratively evaluated and adjusted until convergence is reached. The optimized slot parameters at a constant offset of $d = 0.15$ mm are given in Table I.

III. Measurement Results

For the characterization of the designed slotted array antenna, a transition from WR-12 waveguide to the LWG is necessary (Fig. 9). The transition based on [15] uses a cavity of three LTCC layers to connect a vertically orientated air-filled waveguide to the LWG. The desired LWG height of five layers is achieved

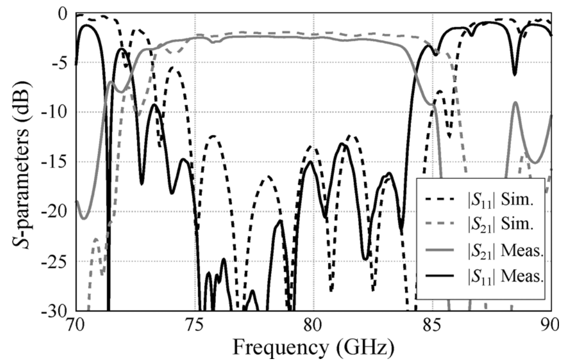


Fig. 10. S-parameters (back-to-back) of broadband WR-12-to-LWG transition used for antenna characterization.

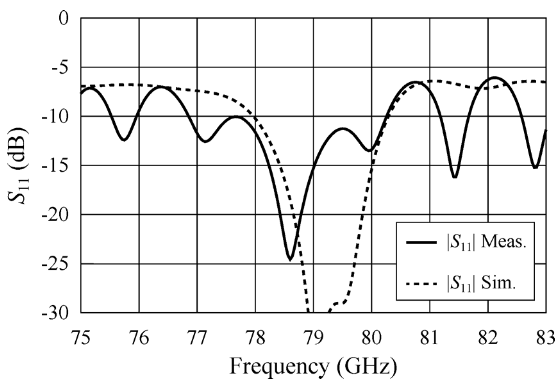


Fig. 11. Return loss of the LWG slotted array antenna.

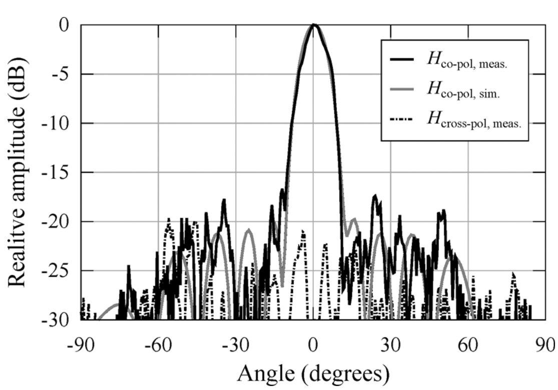


Fig. 12. H-plane radiation diagram of the LWG slotted array antenna at 79 GHz.

using a staircase structure. The measurement of a back-to-back configuration of the transition (Fig. 10) shows a bandwidth of more than 10 GHz with respect to 10-dB return loss.

The measured reflection coefficient of the antenna including the LWG-to-WR-12 transition (Fig. 11) shows a 2.4-GHz impedance bandwidth (10 dB) that is in good agreement with the simulated result not including the transition. The normalized H-plane radiation diagram at 79 GHz depicted in Fig. 12 shows an excellent agreement between simulation and measurement with a 3-dB beamwidth of 10° and a measured SLL of -17 dB. The antenna shows a low measured cross-polarization level being more than 20 dB below the copolarization level in the vicinity of boresight direction. Within the H-plane, the antenna shows a stable radiation pattern (measured $\mathrm{SLL} < -14$ dB) between 78 and 80 GHz with an inevitable beam squint over frequency between $-1°$ and $2°$ due to the serial feeding of the slots. In the E-plane, a very wide beamwidth results from the small dimensions in this plane. The calibrated measured gain of the antenna taking into account the losses due to the feeding line and transition amounts to 9.6 dBi. Considering a directivity of 15.2 dBi, the antenna has an efficiency of 28% caused by the fact that the losses of the applied LTCC material are relatively high.

IV. Conclusion

A resonant laminated waveguide slotted array antenna has been presented. The antenna was realized in a high-permittivity LTCC multilayer. The analysis of a bent longitudinal offset slot showed that besides the slot offset, the bending angle of a slot can also be used to adjust the radiation properties of an antenna. The measured results of the proposed 12-element antenna show excellent agreement with simulations. With the availability of low-loss LTCC material systems, the antenna is a potential candidate for 79-GHz SRR applications.

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