Active Ka-band Open-Ended Waveguide Antenna with Built-in IC Cooling for Use in Large Arrays

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Active Ka-band Open-Ended Waveguide Antenna with Built-in IC Cooling for Use in Large Arrays

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Abstract — This paper presents the design of an open-ended waveguide (OEWG) array element operating between 34 GHz and 36 GHz. The OEWG is coupled to a quarter-wave patch antenna on a PCB, which connects to a millimeter-wave IC via a grounded co-planar waveguide. The radiating element is co-designed with an integrated liquid cooling solution to remove heat from the amplifier and phase-shifting IC. Furthermore, a 4 × 4-element is presented to demonstrate the OEWG design, feed and cooling operation. Although PCB manufacturing deviations were observed in the demonstrator, the realized elements are expected to operate over the entire desired frequency range.

Keywords — Open-ended waveguide, Waveguide launcher, Patch antenna, Ka-band, Phased array, Active cooling.

I. INTRODUCTION

Ka-band radars operating within the range of 33.4 GHz to 36 GHz have found use in a wide variety of applications, ranging from the first automotive radars [1] to airborne synthetic-aperture radar (SAR) [2], military tracking radar [3], airfield surface movement radar (SMR) [4], [5] and meteorological radar [6]. The millimeter-wave (mm-wave) operating frequency enables relatively small-sized devices with good angular and range resolution, albeit with a limited range due to the high rate of atmospheric attenuation.

Thanks to advances in Ka-band array technology for the fifth generation of mobile communication (5G), commercial off-the-shelf (COTS) integrated circuits (ICs) operating around 28 and 39 GHz are becoming more commonly available. These developments are likely to benefit radar technology as well, as standardized components can reduce system complexity, time-to-market and development cost. Single- or multi-channel amplifying and phase-shifting mm-wave ICs closely integrated with the individual radiating elements allow for compact and scalable array designs, where the number of elements can be chosen based on the operation requirements. However, the dense integration of active components, radiating elements and power distribution could generate so much heat to be detrimental to the performance and longevity of an array.

This paper presents the design of a low-profile open-ended waveguide (OEWG) sparse-array element operating between 34 GHz and 36 GHz. The OEWG is launched from a printed circuit board (PCB) using a quarter-wave patch antenna, which connects to an IC containing an amplifier and phase-shifter. The array element is designed with thermal scalability in mind, as the metal waveguide structure also acts as a heatspreader with integrated liquid cooling channels located above the ICs. Furthermore, a realized 4 × 4-element demonstrator array is presented. Since manufacturing deviations were observed on the PCB-based radiating elements, a performance assessment of the unassembled PCBs was made using probe measurements and simulations in CST Microwave Studio (CST MWS).

II. DESIGN

A. Requirements

A list of performance requirements of the Ka-band array element is given in Table 1. The center frequency (f₀) and bandwidth (BW) result from the allocated radio spectrum for radio imaging. To satisfy the ±60° steering requirement, a cosine-shaped element pattern is desired which is defined as

\[
G(\theta) = \begin{cases} 
2(2N + 1) \cos^{2N}(\theta) & \text{for } \theta \leq 90^\circ \\
0 & \text{for } \theta > 90^\circ,
\end{cases}
\] (1)

where \( \theta \) denotes elevation and \( N = 0.5 \) to realize a half-power beamwidth (HPBW) of 120° and 6 dB of directivity [7].

To maximize the space available for the ICs, signal routing, heat dissipation and the OEWGs, the largest possible inter-element spacings \( d_x \) and \( d_y \) are preferred whilst avoiding the appearance of grating lobes. For the beamforming array at a maximum steering angle \( \theta_{\text{max}} \) and for the wavelength at the highest operating frequency \( \lambda_m \) as specified in Table 1, this leads to the criterion [8]

\[
d_x = d_y \leq \frac{\lambda_m}{1 + \sin(\theta_{\text{max}})} \approx 4.463 \text{ mm.} \quad (2)
\]

The effective array spacing can be reduced to half of the element width using a triangular grid, as illustrated in Fig. 1. In a planar array with non-regular element distribution, an example of which is also depicted, this effect can apply for both \( x \)- and \( y \)-directions. As a result, the allowed \( d_x \) and \( d_y \) were doubled, and rounded down to 8.80 × 8.80 mm.

Fig. 1. The effective inter-element distance can be smaller than the element dimensions, as illustrated for example in a triangular grid (left) or sparse array with non-regular grid (right), to avoid the appearance of grating lobes.
Table 1. Element performance requirements.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency</td>
<td>( f_c )</td>
<td>35 GHz</td>
<td>Steering range</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>( BW )</td>
<td>2 GHz</td>
<td>Gain pattern</td>
</tr>
<tr>
<td>Radiation efficiency</td>
<td>( \eta )</td>
<td>90%</td>
<td>Polarization</td>
</tr>
</tbody>
</table>

B. Open-ended waveguide

An OEWG design was chosen for its geometry and promising radiation pattern. Waveguides can coexist with a cooling solution on the same PCB-side, and both can be machined from a single metal block. The waveguide dimensions were selected for a cutoff frequency of 28 GHz, which at 80% of \( f_c \) is low enough to suppress variation of phase velocities within the system bandwidth and high enough to prevent the apparition of higher order modes within the frequency range of interest.

The waveguide length \( L_{ew} \) was designed to be relatively short. This ensures the array element has a relatively low profile and limits metal costs and weight in a large array. A finite corner radius \( r_{cc} \) was chosen to enable two production processes, both standard milling and wire electric discharge machining (wire EDM). The resulting dimensions are given in Fig. 2 and Table 2.

C. Quarter-wave patch feed

An inset-fed quarter-wave patch antenna, shown in Fig. 2a, was chosen to provide the microstrip to waveguide transition from the IC. This concept is similar to the circular patch-to-waveguide interface in [9]. In the design of the shorted quarter-wave patch antenna, electric mirroring is applied with a grounded via fence to halve the size of a standard half-wavelength rectangular patch antenna [10]. This size reduction is required due to the limited area within the waveguide aperture. A grounded coplanar waveguide connects the patch to the ground-signal-ground (SGS) IC pads.

The used PCB substrate, Isola Astra MT77, was chosen for its low loss tangent of 0.0017 and constant relative permittivity of 3.00 [11]. A via fenced formed around the patch to limit mutual coupling and undesired spurious radiation, by preventing the generation of surface waves in the substrate.

The ICs and OEWGs are aligned on the same PCB side, as illustrated in Figs. 2b and 2c, negating the need for shielded feed-vias and multi-layer feeding structures: a grounded co-planar waveguide (CPW) through a 1 × 1 mm aperture in the waveguide wall provides this connection. Consequently, an inset-feed design was used and matching was achieved by tuning the width and length of the insets, \( x_{qwp} \) and \( y_{qwp} \), respectively.

D. Tolerances & Simulation results

The wire EDM technique used to machine the waveguide block can achieve a 20 \( \mu \)m accuracy, and the PCB copper etching and via drilling tolerances are 30 \( \mu \)m and 50 \( \mu \)m, respectively. Dowel pins are used to achieve a total alignment tolerance between PCB and waveguide block of up to 100 \( \mu \)m.

A yield analysis was performed in CST MWS based on the PCB etching tolerances, and simulations have been performed with waveguide misalignments of up to 100 \( \mu \)m in the x-, y- and z-directions. The best- and worst-case S-parameter range per frequency is indicated in Fig. 3. The desired bandwidth is achieved even for the worst-case scenarios. The simulated element pattern is depicted in Fig. 4.

Table 2. Open-ended waveguide and quarter-wave feed patch dimensions.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Size [mm]</th>
<th>Dimension</th>
<th>Size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide width</td>
<td>( W_w )</td>
<td>5.35</td>
<td>Element width</td>
</tr>
<tr>
<td>Waveguide height</td>
<td>( H_w )</td>
<td>1.90</td>
<td>Element length</td>
</tr>
<tr>
<td>Waveguide length</td>
<td>( L_{ew} )</td>
<td>10.0</td>
<td>Substrate height</td>
</tr>
<tr>
<td>Corner radius</td>
<td>( r_{cc} )</td>
<td>0.50</td>
<td>Feedline width</td>
</tr>
<tr>
<td>Aperture width</td>
<td>( W_{ew} )</td>
<td>0.95</td>
<td>Feedline length</td>
</tr>
<tr>
<td>Aperture height</td>
<td>( H_{ew} )</td>
<td>2.00</td>
<td>Feedline gap</td>
</tr>
<tr>
<td>Patch width</td>
<td>( W_{qwp} )</td>
<td>3.50</td>
<td>Via diameter</td>
</tr>
<tr>
<td>Patch length</td>
<td>( L_{qwp} )</td>
<td>1.13</td>
<td>Fence spacing</td>
</tr>
<tr>
<td>Patch insert width</td>
<td>( x_{qwp} )</td>
<td>0.55</td>
<td>Channel radius</td>
</tr>
<tr>
<td>Patch insert depth</td>
<td>( y_{qwp} )</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>
The milled metal block containing the OEWG array, with the cosine pattern defined in (1) as reference.

After manufacturing of the PCBs, displaced vias were visible surrounding the quarter-wave feed patches as illustrated in Fig. 6a. The copper etching dimensions were within specification. An X-ray inspection showed that in some boards vias were shifted in the positive (+) indicated direction, and in other boards the displacement was in the negative (-) direction. The mirrored displacements is due to the panelization of the PCB manufacturing process. As this displacement changes the effective patch length, the performance was verified using probe measurements on the bare PCB and CST MWS simulations (depicted in Figs. 6b and 6c, respectively) before assembly of the ICs and other components.

The bare GSG IC pads were used to land the probe on, to most accurately match the designed interface. The measurements were performed with a 500 µm SG probe, as no suitable GSG probe was available. To account for this unconventional measurement, a simulation model of the OEWG array and probe was made in CST MWS. The measured and simulated input-impedances are shown for positive and negative via-shifts in Figs. 6d and 6e, respectively. In both cases, the measurements match the simulations well. The resonance frequency of the quarter-wave patch is noticeably affected by the via displacement, which can be seen at the nominal 34 GHz resonance point, which shifts 0.5 GHz down and up due to the via shifts in 6d and 6e, respectively.

Based on the determined via positions and the measurement results, new tolerance simulations were performed to assess the impact on the individual elements and on the 4 x 4 array. The result of these simulation are presented in Fig. 6f and 6g for positive and negative via displacements, respectively. The input reflection and mutual coupling have deteriorated with respect to Fig. 3. Nominally, without any waveguide misalignment, the required bandwidth is still achieved. However, the displaced vias have made the element more sensitive to waveguide misalignments, meaning special care must be taken during assembly for future experiments.
IV. Conclusion & Future Work

This contribution has presented the design of a Ka-band OEWG array-element for radar applications. The element design accommodates a scalable liquid-cooling solution to ensure large-scaled arrays with amplifiers, phase-shifters and other circuitry remain at a low operating temperature. The use of a shortened quarter-wavelength patch antenna to feed the OEWG achieves sufficient bandwidth for the radar application, and simulations of the design indicate good robustness against waveguide misalignment and copper etching tolerances.

The via displacement was more severe than initially specified, which may have been caused by warpage or shrinkage of the MT77 substrate during processing steps. Based on probe measurements and simulations, the elements are still expected to perform well despite the displaced vias. However, the input-reflection bandwidth has become more sensitive to waveguide alignment. A more thorough investigation of the via displacement, with more production samples than available at this time, may prevent the occurrence in the future. Further research steps include the component assembly on the PCBs and over-the-air measurements to verify the designed array elements and cooling performance.

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