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Low-profile Direction Finding System at the Ku-band using SIW Horn Antennas

Marc Esquiús-Morote¹, Jean-François Zürcher¹, Juan R. Mosig¹ and Benjamin Fuchs²

The interest in mm-wave components and systems is currently increasing, as new wireless applications are being introduced in this frequency range. To provide widespread commercial solutions, a low cost technology suitable for mass production is needed. A very promising candidate for implementing high performance, low cost and reliable mm-wave components is the Substrate Integrated Waveguide (SIW) technology [1]. SIWs are integrated waveguide-like structures fabricated by creating rows of metallized vias in a dielectric substrate, which electrically connect two parallel metal plates. The most significant feature of this technology is the possibility to integrate several types of components in the same substrate, including passive components (filters, couplers, etc.), active elements (oscillators, amplifiers, etc.) as well as antennas [1]-[7].

The SIW technology also provides the advantages of high density component integration, low-profile and lightweight. These aspects make SIW attractive for implementing flush-mounted antenna systems for vehicles. Then, the antenna system barely affects the vehicle aerodynamic and aesthetic profiles, thus minimizing the drag. In the case of systems working in the azimuthal plane, e.g., for inter-vehicle communication or Direction Finding (DF) applications, end-fire radiating elements are needed. Depending on the signal polarization, different types of SIW antennas have been proposed: tapered slots or quasi Yagi-Uda antennas for the horizontal polarization [4], and H-plane apertures or horn antennas for the vertical one [5]-[7]. The latter are of particular interest for applications working near the ground, because horizontally polarized signals are greatly attenuated in these environments. An illustrative example of how to mimic a conventional H-plane horn antenna with SIW technology is shown in Figure 1.

Motivated by all these advantages, this article presents a complete Ku-band low-profile DF system using SIW horn antennas. More specifically, a circular array of 8 SIW horns is used to provide full 360° coverage of the azimuthal plane. These antennas are then interconnected with commercial Monolithic Microwave Integrated Circuit (MMICs) to obtain beam-switching capabilities and to estimate the Direction of Arrival (DoA). The whole structure remains low-profile, lightweight and low cost, i.e., suitable to be integrated in airborne or terrestrial vehicles.

¹ The authors are with the Laboratoire d'Electromagnétisme et d'Acoustique (LEMA), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland.

² The author is with the IETR/University of Rennes I, 35042 Rennes Cedex, France.

SIW Horn Antennas

The SIW horn antenna is a widely used antenna topology in order to radiate end-fire in system-on-substrates designs [4]-[5]. However, its main drawback is the degradation of both radiation and matching performances when the substrate thickness h is much smaller than the free space wavelength λ_0 [6]. Usually, for $h < \lambda_0/6$, there is a strong mismatch between the antenna aperture and the air which results in unwanted back radiation and poor matching. This situation is frequently encountered at frequencies lower than 20 GHz when commercial substrates (whose thicknesses are typically lower than 2.5 mm) are used. This is why SIW horn antennas are usually not considered for applications at the Ku-band or below.

To overcome this limitation, a novel design for SIW horn antennas has been proposed in [6],[7]. The main idea behind this solution is to etch a transition after the horn aperture in order to reduce the mismatch between the aperture and the air (see Figure 2). Excellent performances in terms of matching and radiation over a wide frequency range have been reported while the antenna thickness h remains thinner than $\lambda_0/10$. Simple design rules and examples of this new type of SIW horns are also given in [6],[7]. In addition, these horns are tapered following an elliptical shape to obtain a more compact design for a given directivity by combining several TE modes.

In this article, these novel compact and thin SIW horn antennas are used as basic elements of a low-profile beam-switching antenna array for DF applications. Since electronic components are required to carry out this functionality, the interconnection between these antennas and commercial MMICs is investigated in the next section.

Interconnection SIW Horn Antenna – MMICs

Planar transmission lines, such as microstrip lines (MSL) and coplanar waveguides are favorable to the integration of microwave system. More specifically, MSLs are the most viable option when encapsulated MMICs are used. Thus, a transition SIW-MSL must be designed to create a fully integrated system.

The whole system is designed to work at the Ku-band, specifically at the central frequency $f_0 = 15$ GHz. In order to choose the most suitable type of transition, the antennas substrate (SIW substrate) must be compared with the one required for the electronics (MSL substrate). On the one hand, the type of SIW horn antenna described in [7] requires a low permittivity

substrate. A good option is 1.91 mm Rogers TMM3 substrate ($\epsilon_r = 3.39$) [8]. On the other hand, thin and high permittivity substrates are preferred to place MMICs since their connectivity with MSLs is more convenient and they allow for a higher degree of integration. Moreover, if they are encapsulated in QFN packages, usually a 50 Ω input pin of width 0.3-0.4 mm is available. Thus, a 0.38 mm Rogers TMM10 ($\epsilon_r = 9.56$) was chosen on which a 50 Ω MSL has a width $M_w = 0.34$ mm.

Due to the large difference between the thicknesses of both substrates, a vertical transition is chosen to meet both electromagnetic and mechanical constraints. Several SIW-MSL vertical transitions offering similar performances have been proposed in the literature. They are mainly based on probe feeding and slot coupling [9],[10]. In particular, the slot coupling transition eases the assembling process and is more robust to tolerances. Therefore, in our case, a slot in the common metal plane between the MSL and SIW is opened for the energy to couple between these two structures (see Figure 3). T_w defines the slot width, T_L the slot length and M_s the microstrip stub.

In a slot coupling transition, the forward and backward travelling waves of the electric field excited by the slot are in opposite direction, i.e., the slot must be opened as close as possible to the shortest end of the SIW for a maximum power transfer [10]. Despite the large differences in permittivity and thickness, this transition offers a good wideband behavior. Its performances are shown in the next Section along with a three-element SIW horn array prototype.

Three-element SIW Horn Array Prototype

A three-element SIW horn antenna array was manufactured to test the antenna performances when fed by the previous multilayer transition. The measurements extracted from this prototype are then directly used to design the complete circular array of 8 elements. In practice, one element of the complete array will have the same behavior as the central one in this 3-element prototype since its performances are mainly affected by the adjacent horns.

Each SIW horn has the same dimensions as in [7] and, after an optimization process, the SIW-MSL transition dimensions were chosen as [mm]: $T_w = 0.6$, $T_L = 8.1$ and $M_s = 1.7$. Finally, in order to obtain an overlapping between adjacent beams at around -3 dB, the horns are placed on a circle of 52 mm radius with a 45° separation. The layered view of the

prototype is shown in Figure 4. In this case, instead of MMICs, three SMA connectors were placed after the MSLs to accurately measure the antenna performances.

The measured S parameters are plotted in Figure 5. All three SIW horns present a reflection coefficient below -10 dB over a 20% bandwidth (between 14.2 and 17.5 GHz). Thanks to the practically enclosed structure of a SIW horn antenna and a good design of the multilayer transition, the mutual coupling between horns is practically negligible. Indeed, the measured values of $|S_{12}|$ are below -40 dB over the whole frequency range.

The measured H-plane radiation patterns of the three SIW horns at f_0 are superimposed in Figure 6. Despite their low-profile, the horns are able to considerably focus the energy frontwards achieving a front-to-back ratio above 15 dB. The -3 dB beam overlapping required for beam-switching applications can also be observed. The efficiency of the central horn is 85% with a realized gain of 5.6 dBi. Moreover, a cross-polarization level below -20 dB was also measured.

After the experimental validation of the SIW horn antenna array, the electronic system can be designed.

Electronic System Design

In this section, the electronic components used to implement a beam-switching antenna system with DF capabilities are described. A beam-switching antenna is an antenna array that can form a set of predefined beams. Once a beam is selected using switches, its received signal is downconverted and then processed. Although this type of systems is not as flexible as an adaptive array, its main advantage is simplicity and, therefore, low cost. All processing is done in the RF domain so that only one signal has to be downconverted: this is a significant price-wise advantage since the circuits for downconversion are among the most expensive ones in today's wireless systems (this is particularly true when working at mm-wave frequencies). Moreover, it is important to mention that the performances offered by a beam-switching system are usually enough for many common applications [11]. Hereinafter, the design and prototype of a receiving system is presented.

The block diagram of the DF electronic system is shown in Figure 7. First, a MicroController Unit (MCU) selects the signal coming from the desired antenna using RF switches. This signal is then split with a directional coupler between the RF output and the control loop. The

RF output is the port from where the information carried by the received signal is read. The control loop signal is converted to a proportional DC voltage by means of a Logarithmic Detector (LD) and sent back to the MCU. Finally, after sampling and processing the different antenna signals, the MCU computes the DoA. Amplifiers are also used after the switches and the coupler to compensate for losses.

All RF electronics were supplied by Hittite Microwave Corporation [12] which provides components with good performances in our frequency range of operation. In particular, three HMC641LC4 SP4T switches, two HMC383LC4 amplifiers and one HMC948LP3E logarithmic detector are used. All these components are QFN GaAs MMICs largely capable of handling the common power levels in a receiving antenna system. It is also important to mention that absorbent material (ECCOSORB GDS-U [13]) is needed to suppress the strong oscillating trend of the amplifiers.

A simple and low-cost Peripheral Interface Controller (PIC) is used as MCU, the PIC16F88. An internal 10-bit analog-to-digital converter is already included in this PIC which, in our case, is employed to convert the analog output of the logarithmic detector. The control signals for the switches, however, cannot be directly generated by the PIC. As any common microprocessor, this PIC works with a 5/0 V logic while the SP4T switches work with 0/-5 V logic. A standard multiplexer (MC14053BD) is then used to convert the logic level.

Finally, the PIC is programmed to sample the 8 different signals, compare them and compute the DoA. The system functionality is assessed by means of a simple amplitude comparison algorithm based on the measured radiation patterns of Figure 6. In the next Section, the complete system is presented along with measurement results and some practical remarks.

Complete Direction Finding System

The complete system is shown in Figure 8. The dimensions and materials used for the SIW horn antennas and the transitions are the same as in the prototype of Figure 4. Nevertheless, the radius of the antenna array was increased to 90 mm in order to accommodate all the required RF and DC components.

A shielding structure composed of a brass wall and a copper cover is also designed in order to protect the electronics. It is extremely important to protect all the RF components since incoming high frequency signals can easily couple to the transmission/feeding lines yielding

malfunctioning or even damaging some sensitive components. For the same reason, the two feeding lines of this prototype (+5 and -5V) are brought inside the shielding using feed-through connectors. Some absorbent material (ECCOSORB MCS-U) is also glued at the interior part of the top cover to damp any potential cavity resonance [15]. For demonstration purposes, LED diodes are placed at the brass wall, one in front of each antenna, in order to indicate which antenna is receiving the highest signal level. The output pins of the PIC are then used to drive these LEDs (see Figure 8).

The complete system was tested in the facilities of the Laboratory of Electromagnetics and Acoustics (LEMA) at the EPFL. First, a calibration procedure was carried out: although the MSLs coming from each antenna were designed of the same length (same losses), the insertion losses of the SP4T switches were slightly different for each port. To account for this difference, the signal strength received by each antenna under the same conditions was measured at the RF output and the difference compensated later by post-processing in the PIC.

The sensitivity of the system is mainly limited by the sensitivity of the logarithmic detector. For a reliable DoA estimation, a signal strength of -65 dBm is required at the antenna level. Then, by using the amplitude comparison algorithm, the maximum DoA error is of $\pm 3^\circ$ between 14.5 and 15.5 GHz. The system consumes around 300 mA (the major part is due to the amplifiers and the logarithmic detector) and its total weight is 220g (including the shielding structure).

Conclusions

A fully operational direction finding system based on SIW horn antennas has been proposed and experimentally verified. Thanks to the SIW technology, the antenna array and thus the whole system is low-profile, lightweight and low cost when compared to similar solutions at the Ku-band. A simple way to efficiently interconnect these SIW antennas with commercial MMICs is also explained and tested.

The proposed system demonstrates the viability and reliability of the SIW technology for implementing high performance commercial solutions. In particular, this system is suitable to be flush-mounted in airborne or terrestrial vehicles. Although the system has been demonstrated for a simple receiving direction finding application, the concept is also full of promises for more ambitious applications requiring high data rate transmissions.

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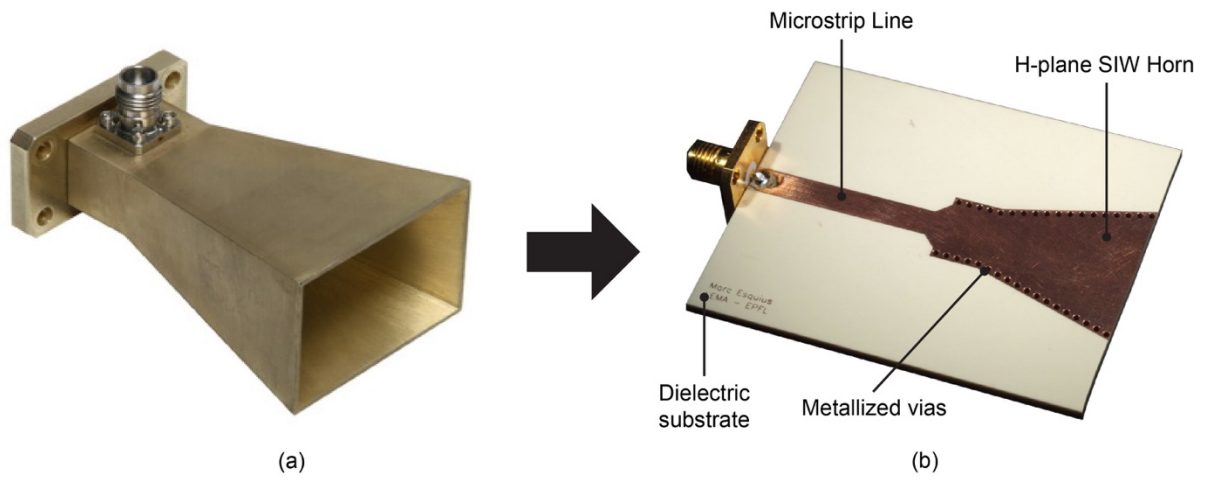


Figure1

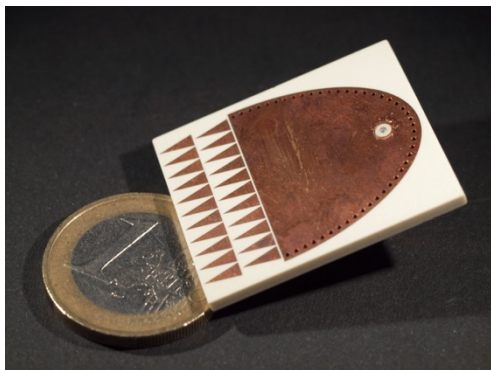


Figure 2

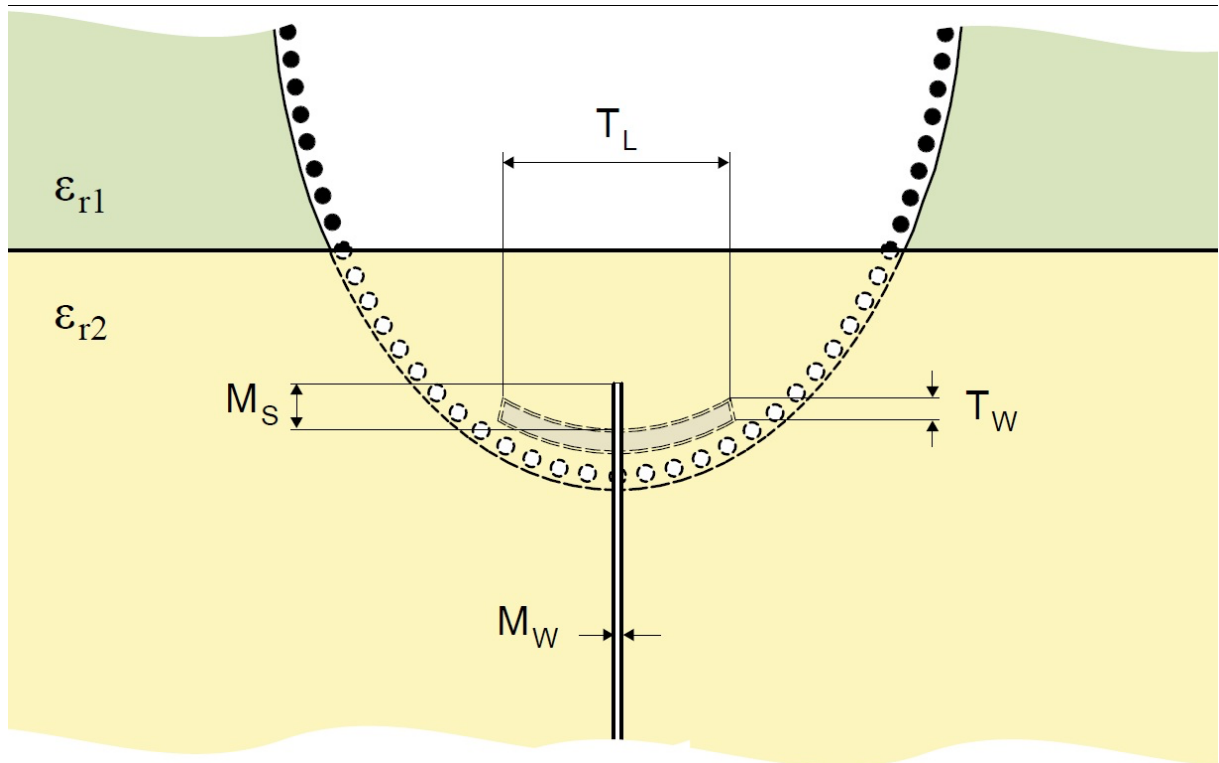


Figure 3

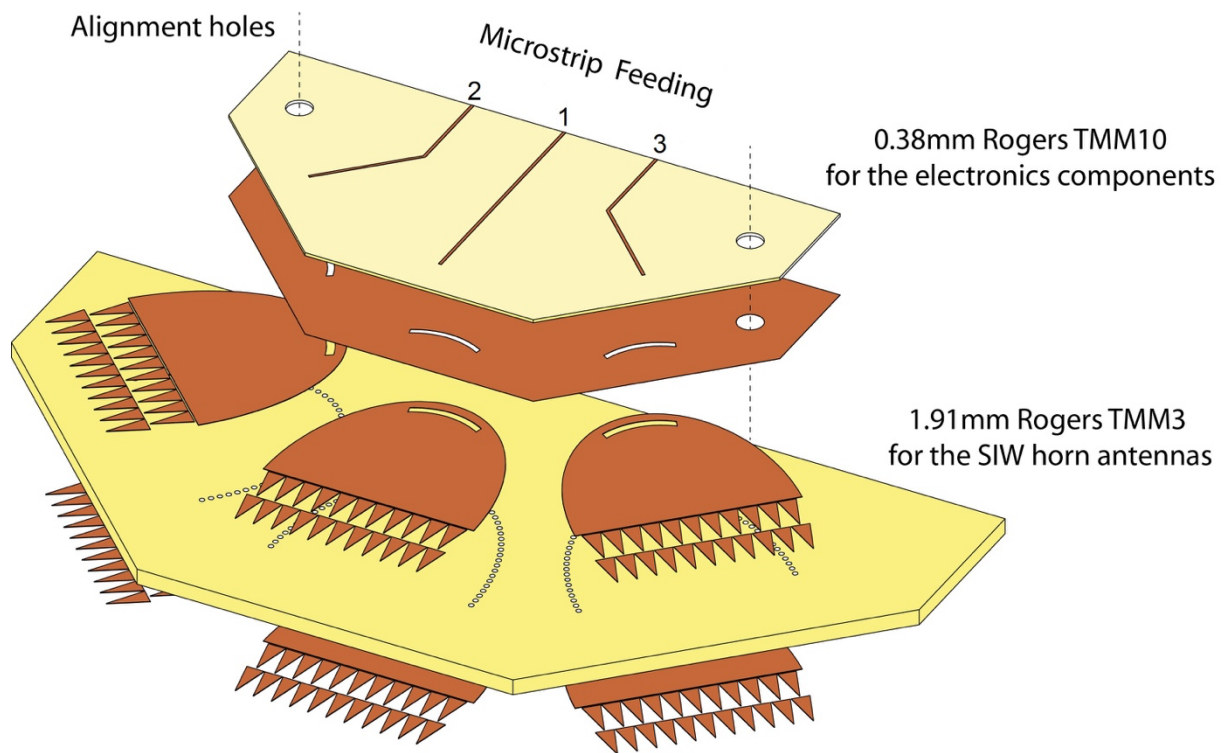


Figure 4

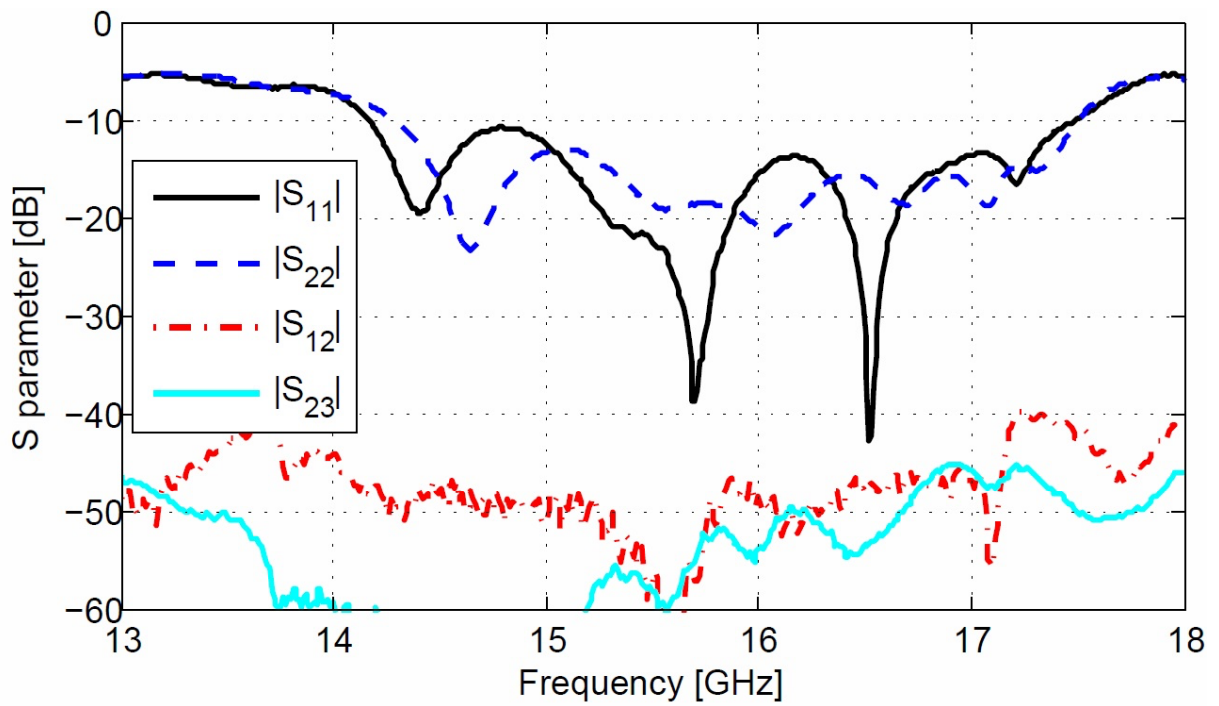


Figure 5

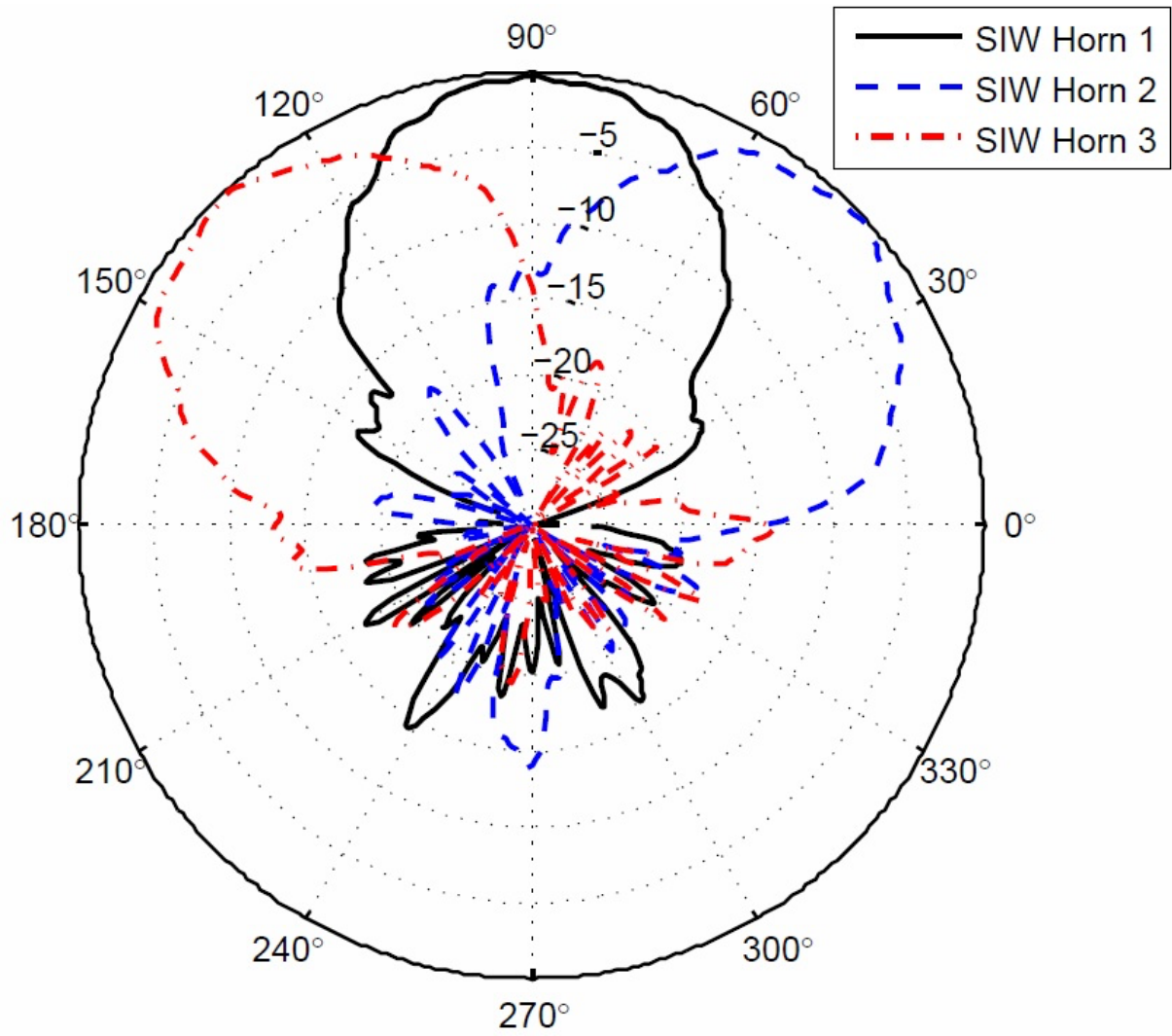


Figure 6

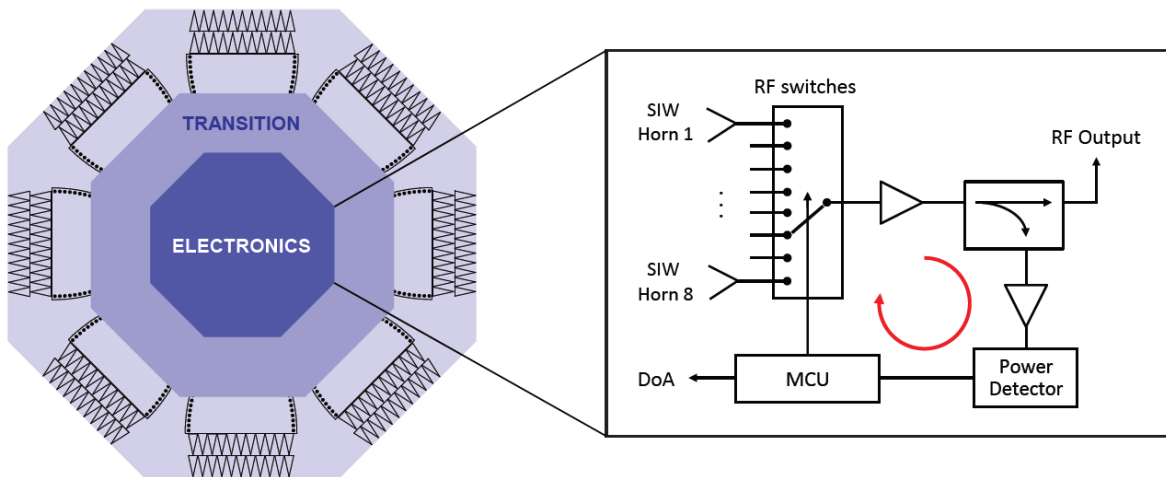


Figure 7

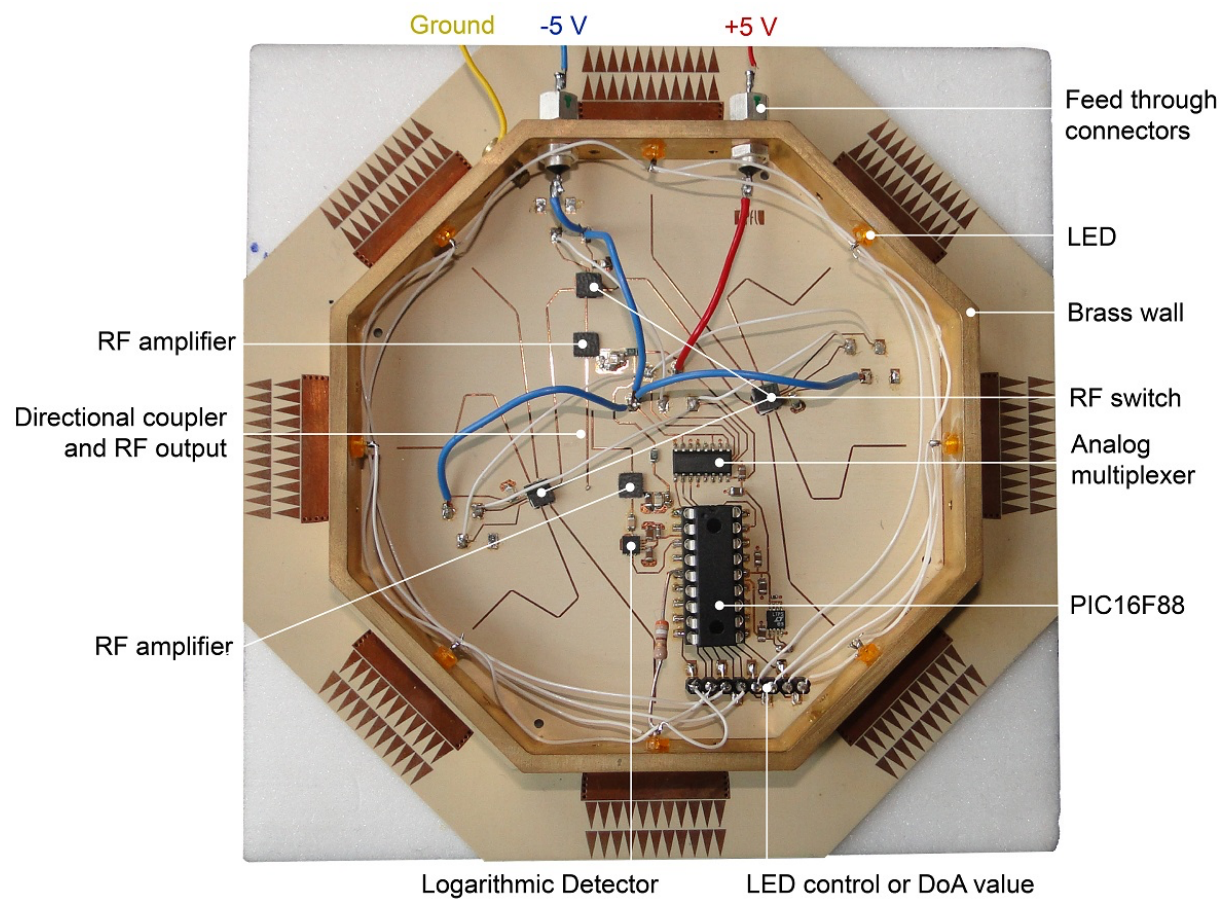


Figure 8