Admittance Matching of 60 GHz Rectangular Dielectric Resonator Antennas for Integrated Impulse Radio

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***Abstract*—Methods to achieve admittance matching of rectangular dielectric resonator antennas intended for 60 GHz impulse radio are reported. The motivation is to find a suitable antenna that may be integrated in the V-band gated tunnel diode wavelet generator, replacing its tank circuit and forming a low complexity transmitter. Probed one- and two-port scattering parameter measurements have been performed to characterise the fabricated antennas. Changing the feed structure from a tapered dipole to an offset fed and tapered slot, a change from capacitive to inductive characteristics is observed, and the matching to the gated tunnel diode is improved. Deembedded admittance resonance frequencies of fabricated antennas were found at 53.6 and 52.2 GHz for dipole and slot fed antennas, respectively. Characterising the transmission link between dipole fed antennas, a maximum antenna gain of 10.5 dBi and a 3 dB power bandwidth of 1.5 GHz were found at 53.3 GHz.**

I. Introduction

Wireless communication at 60 GHz is attractive for operation at high bit-rates and integrated impulse-based systems offer broadband low-power consumption transmitter solutions, requiring compact and energy efficient integrated antennas. Coplanar microstrip or waveguide antennas on electrically large semiconductor substrates are not feasible for impulse operation as they disperse the transmit signal into uncontrollable high order propagating modes [1]. High, V-band, operation frequency introduce the possibility to cut a dielectric resonator antenna (DRA) from the substrate and use an electrically small probe to feed it. DRAs have been studied for their effective radiation characteristics, small size and diversity of compatible feed methods. Placed on a mirror groundplane for increased directivity and compactness, a high performance and scalable antenna may be achieved.

We are targeting a rectangular DRA for our gated tunnel diode (GTD) wavelet generator, which is fabricated on 650 μm thick semi-insulating GaAs. Successful integration with an antenna that actively tunes the GTD to resonance at 60 GHz will produce an energy efficient wavelet transmitter operable in impulse mode by e.g. pulse position, frequency or binary phase shift keying [2], [3]. Constructing a transmitter using a matched antenna, without any matching network or buffer, has advantages such as low power loss and minimal integration complexity.

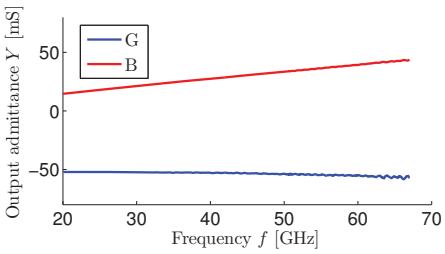

Fig. 1. Deembedded output admittance measured on a 10×18 μm^2 GTD, having an admittance $Y = -55 + 39$j mS at 60 GHz.

In this work, different antenna feed structures on rectangular DRAs are fabricated and the admittance matching to the GTD evaluated. Also, transmission measurements between dipole fed DRAs demonstrate the functionality of the fabricated antennas.

II. GTD wavelet transmitter

A resonant tunnel diode (RTD) may be utilised as the active component in an oscillator circuit since it possesses the physical property of negative differential conductance [2], [4]. The GTD is fabricated through incorporation a third terminal in the form of a permeable gate adjacent to the double barrier heterostructure of an AlGaAs/GaAs RTD. This has been made possible through the method of epitaxial GaAs overgrowth over ultra-thin tungsten wires [5]. Since the magnitude and sign of the GTD output conductance is related to the electrostatically controlled RTD area, it may be tuned using the gate bias [6]. Loading the GTD output with a tank circuit, it is possible to rapidly gate the circuit into and out of an oscillating state, producing down to 33 ps long 60 GHz wavelets directly from a baseband signal [3].

The admittance of, and hence matching of an antenna to, the GTD output is dependent on the defined active device area and

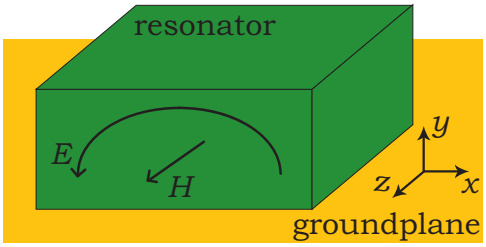

Fig. 2. Schematic of a rectangular dielectric resonator and the coordinate system used. Superimposed on the structure are electric E and magnetic H fields of the fundamental mode mirrored in a groundplane.

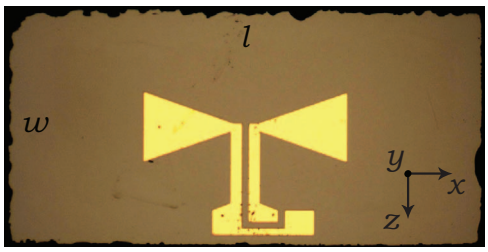

Fig. 3. Optical micrograph of a dipole feed with coplanar microstrip input on top of a 1300×650 μm^2 GaAs DRA.

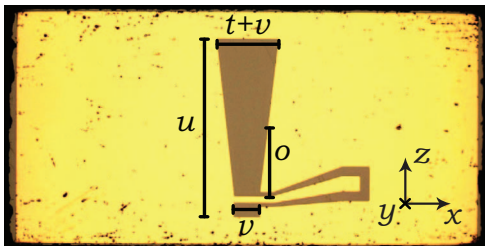

Fig. 4. Optical micrograph of a slot feed with coplanar waveguide input in a groundplane on a 1300×650 μm^2 GaAs DRA, also shown are definitions for slot dimensions.

bias point. Deembedded output characteristics of a 10×18 μm^2 GTD measured at bias $V_{\mathrm{CE}} = 0.94$ V and $V_{\mathrm{GE}} = -0.50$ V is displayed in Figure 1, revealing a capacitive output admittance in the current implementation where $Y = -55 + 39\mathrm{j}$ mS at 60 GHz. In the wavelet generator setup, the GTD is tuned to resonance by an inductive integrated coplanar short-circuit stub [2], [3]. Important in the selection of antenna is hence that it has an inductive and smooth susceptance which added to the GTD output yields a clean resonance condition at 60 GHz.

III. Antenna Design

We treat the design of the DRAs as two separate problems. The dimensions of the resonator is assumed to be the main factor to determine the resonance frequency of the antenna, while the input admittance is tuned by the feed used to access the resonant mode, as will be discussed below.

A. Resonator

Rectangular dielectric resonators have non-confined TE-modes that efficiently radiate their energy to the surroundings. The principles of radiation from the fundamental mode in such a resonator have been reported together with design formula and experimental results [7], [8]. A schematic picture of a rectangular resonator geometry is presented in Figure 2, including a sketch of the electric and magnetic fields of the fundamental mode mirrored in the xz-groundplane.

The following design formulas of the dielectric waveguide model from [8] are used to obtain a preliminary design which is later refined using full wave simulations. In the x and y dimensions, the wavenumbers k_{x} and k_{y} of the fundamental resonant mode are simply fitted to the length l and height h of the mirrored resonator

$$k_{\mathrm{x}} = \frac{\pi}{l} \tag{1a}$$

$$k_{\mathrm{y}} = \frac{\pi}{2h}. \tag{1b}$$

A more intricate expression is used to relate the width w and wavenumber k_{z} of the resonator in the z direction

$$k_{\mathrm{z}} \tan \frac{k_{\mathrm{z}} w}{2} = \sqrt{(\epsilon_{\mathrm{r}} - 1)k_0^2 - k_{\mathrm{z}}^2}, \tag{2}$$

where $k_0 = 2\pi f_0/c$ is the wavenumber in free space. Applying the above expressions to the separation equation

$$k_{\mathrm{x}}^2 + k_{\mathrm{y}}^2 + k_{\mathrm{z}}^2 = \epsilon_{\mathrm{r}} k_0^2, \tag{3}$$

the width w of a resonator with known length l and electrical height $2h$ may be calculated for the desired resonance frequency f_0.

At 60 GHz, a mirrored $h = 650$ μm high and $l = 1300$ μm long GaAs resonator, $\epsilon_{\mathrm{r}} = 12.9$, must then be $w = 450$ μm wide. Early experimental results on dipole fed DRAs indicated that a width $w = 650$ μm provides a better implementation at 60 GHz, although it according to theory would resonate at 56 GHz.

B. Feeds

Feeding of the rectangular resonator is done with an electrically small metallic structure positioned directly onto its side. Probes that mimic the fields of the targeted mode are desired in order to get a good electromagnetic coupling.

A dipole placed on top of and along the length of the resonator, to stimulate a parallel electric field, has been investigated previously through simulations [9]. This feeding solution turned out capacitive at the dielectric resonator resonance frequency as a dipole is an inherently capacitive structure below its resonance frequency. The antenna can be made inductive by shunting it with a small inductive strip, which corresponds to a simple matching network, which however will short circuit the radiation resistance. Here, we fabricated and studied dipole fed DRAs with tapered arms to increase their bandwidth, as shown on the optical micrograph in Figure 3.

A slot in an infinite groundplane is the complementary structure to a dipole, having qualitatively inverse impedances [10]. Feeding the resonator with a slot, oriented along the width of the resonator, should hence turn out as an inductive

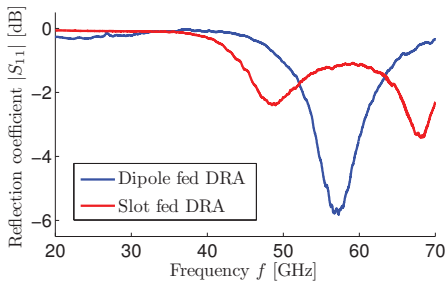

Fig. 5. Deembedded reflection coefficient measurements on fabricated 1300×650 μm^2 GaAs DRAs with dipole feed and a $t = 100$ μm tapered and $\delta = 80\%$ offset fed slot.

antenna more suitable to match the capacitive GTD. This also allows for the groundplane to be deposited directly onto the resonator as a part of the feed structure, disturbing the targeted mode less than the dipole feed. Admittance modification may be performed by variation of the length u, width v and tapering t of the slot.

Feeding at an offset position in the slot has been simulated to suppress resonance undulations in the antenna susceptance [11]. In order to verify this result on slot fed DRAs, feed structures with up to $\delta = 2o/u = 90\%$ relative offsets were designed. An optical micrograph of a fabricated DRA with a $u = 500$ μm long, $v = 75$ μm wide, $t = 100$ μm tapered and $\delta = 80\%$ offset fed slot is shown in Figure 4.

IV. Fabrication

Fabrication of the designed feed structures is performed using standard deep-UV lithography followed by thermal evaporation of metal and a lift-off process. Positive S1813 image resist on LOR 7B is used to define the antenna feed pattern consisting of a 8000 Å gold layer on an adhesion layer of 50 Å titanium [12]. This allows for the high conductivity feed to be tightly bonded to the resonator body, eliminating any parasitic effects that may be introduced from an air gap between feed and resonator [13].

Defining the rectangular GaAs resonator body from the substrate with Cl_2-based dry etching has been tested [9], but the process is challenging since it requires a very deep etching. The sample with predefined feed structures is instead sawed into 1300×650 μm^2 dies with a semiconductor saw.

V. Characterisation

Scattering parameter measurements were performed using a network analyser with calibrated 100 μm pitched GSG measurement probes. Antennas must hence be mounted on a carrier with their inputs facing up towards the alignment microscope.

Dipole fed DRAs are glued to a groundplane on a Si wafer using a cyanoacrylate-based adhesive, Loctite 420 with capillary function. Slot fed DRAs are instead glued onto a 2 mm thick PMMA plane, $\epsilon_r \approx 4$, through which they may radiate while being separated approximately 4 cm from the probe station chuck.

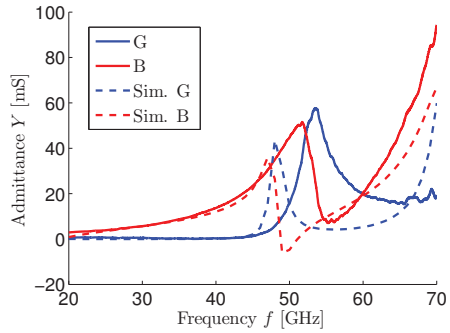

Fig. 6. Deembedded admittance measured on a dipole fed DRA, compared with an Efield simulation. Fundamental resonance is at $f_0 = 53.6$ GHz with admittance $Y(f_0) = 36.2 + 23.9$j mS.

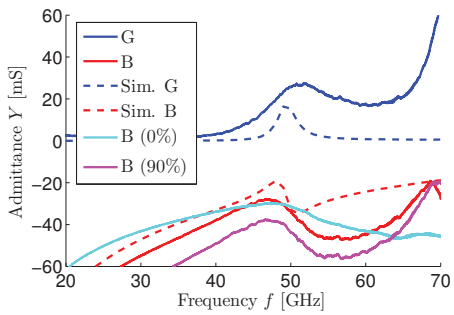

Fig. 7. Deembedded admittance measured on a slot fed DRA, compared with an Efield simulation. Fundamental resonance is at $f_0 = 52.2$ GHz with admittance $Y(f_0) = 22.1 - 43.2$j mS. Susceptance of slot fed DRAs with the extreme point offsets, $\delta = 0$ and 90% are also shown.

Characterising the transmission between DRAs, a barrier of aluminum foil was inserted between adjacent antennas under test and a piece of Cu-plated printed circuit board was positioned above the antennas and used as a signal reflector. This setup blocks the direct path between the adjacent antennas and instead introduce a reflected link, allowing transmission measurements at broadside radiation over variable propagation distances $r = 83$ to 143 mm, corresponding to a few tens of free space wavelengths.

A. Reflection coefficient

Deembedded input reflection coefficient measurements on the dipole and slot fed DRAs in Figures 3 and 4 are presented in Figure 5, obtained with a 20 mS reference at a source power of -6 dBm. The dipole fed DRA have a relatively strong resonance peak, $|S_{11}| = -5.81$ dB at 57.3 GHz, while the slot fed DRA have two resonant peaks within the measurement interval, $|S_{11}| = -2.39$ dB at 48.6 GHz and $|S_{11}| = -3.41$ dB at 68.1 GHz, respectively.

B. Admittance

Admittance of the fabricated DRAs is extracted from the reflection coefficient measurements, showing the influence of dipole and slot feeding in Figures 6 and 7, respectively. Also shown are full wave simulation data from the method

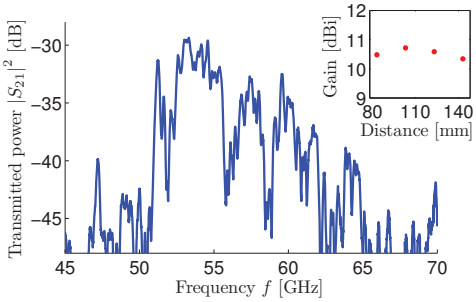

Fig. 8. Relative power level transmitted over $r = 143$ mm distance between dipole fed DRAs around the 53.3 GHz maxima. Inset show calculated maximum antenna gain, $G = 10.5$ dBi, at four equal increment distances.

of moments solver Efield (`www.efieldsolutions.com`), generally underestimating the bandwidth and conductance of the DRAs at resonance. The simulations predict the fundamental resonance frequency in the slot fed DRA reasonably well, while the resonance frequency in the dipole fed DRA is underestimated. The latter is likely a result of the metal connectors to the input waveguide on the fabricated dipole fed DRA, pushing the resonant mode away from the resonator top surface and reducing the electrical size of the resonator. The lower fundamental resonance frequency of the slot fed DRA may be explained by its smaller ground plane, allowing a more non-confined mode than with an infinite mirror. Measured input susceptance of antennas with both zero and maximum feed offsets are also shown in Figure 7, both undulating at their resonance frequencies.

C. Transmission

Positioning a signal reflector at different lengths from the mounted dipole fed DRAs, transfer characteristics as shown in Figure 8 were measured. The 3 dB power bandwidth of the link at 53.3 GHz is found to be 1.5 GHz, though this would be more than doubled if not for some sharp fadings. Antenna gain may now be calculated as half the difference between the theoretical free space pathloss (FSL) and the measured power maximum, which is shown on the Figure 8 inset for four equal increment distances. The shift in magnitude of link loss corresponds well to that of FSL, 45.4 to 50.1 dB at 83 to 143 mm transmit distance, and use of Friis transmission formula results in a constant maximum gain level $G = 10.5$ dBi at 53.3 GHz, confirming that the measured transfer of energy is achieved through far-field coupling between the antennas. This gain value is somewhat higher than the 5–7 dBi expected from a small dipole mirrored in a groundplane [14]. The foil barrier placed adjacent to the DRAs under test and coupling from the resonators to the probes may contribute to the increase in maximum gain.

VI. Conclusions

Dipole and slot fed rectangular DRAs have been fabricated and characterised, revealing that the two feed schemes result in qualitatively inverse input admittances. We observe susceptance resonance undulations for all fabricated slot fed DRAs, independent on offset feeding of the electrically small feed slot. Dielectric waveguide design formulas were found to overestimate the resonance frequency of the fabricated DRAs. Inductive slot feeding of the DRA results in a resonance frequency close to simulations, while the capacitive dipole fed DRA resonate at higher frequencies, likely depending on the metal connectors to the input waveguide confining the mode further. A good susceptive match to the GTD may be performed with the tapered and offset fed slot DRA, although it need to be tuned to 60 GHz. Transmission experiments confirm the antenna functionality and show a maximum gain of 10.5 dBi for the dipole fed DRAs in the current measurement setup. Antenna gain can be further increased by combining several of the antennas considered in this paper as elements in an array antenna.

Acknowledgment

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