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Broadband Slot Feed for Integrated Lens Antennas

Jorge R. Costa, *Member, IEEE*, and Carlos A. Fernandes, *Member, IEEE*

***Abstract*—This letter presents a new broadband printed antenna based on crossed exponential slot configuration, which presents very good linear polarization. It is compact and especially adequate for integrated lens antenna feeding at millimeter waves and submillimeter waves. The concept is validated with experimental results.**

***Index Terms*—Integrated mixer, lenses, printed broadband antenna, stable linear polarization.**

I. Introduction

THE existence of integrated quasi-optical receivers with bandwidths on the order of 100% [1] motivates the development of new submillimeter-wave antennas that can match such bandwidths and further improve other specific requirements from quasi-optical systems. Integrated axial-symmetric double-shell dielectric lens antenna solutions are being studied with this objective in the framework of the ILASH project [2].

Due to fabrication constraints at submillimeter waves, it is highly convenient that the integrated lens feed can be implemented within one or two layers of metallization at the base of the lens, which precludes the use of feeds with depth (e.g., waveguides or corrugated horns). Printed antenna technology is the natural option. Double slots are a common linear polarization (LP) solution for integrated lens feeds but they are narrow band [3]. The self-complementary printed log-periodic antenna is the classical LP wide-band solution for integrated lens feeding [1]. However, its polarization direction is not stable with frequency. The cross-polarization level oscillates with frequency, ranging between -15 and -5 dB in [1]. The antenna configuration proposed in this letter is more compact, yields slightly higher gain, and can provide far better cross-polarization characteristic.

For concept validation, two different scaled prototypes of the proposed antenna were designed, fabricated, and measured: one prototype was designed for standalone operation across the 1.5–4 GHz bandwidth radiating into air, fed by coaxial cable; a second prototype, integrated with a mixer circuit was designed to feed a MACOR elliptical lens in the 30–70 GHz band. The choice of coaxial feeding for the first prototype at lower frequencies enables direct measurement of the antenna impedance characteristic versus frequency, something that is not so easy when the antenna is integrated with a mixer circuit and lens, as in the second prototype. The second prototype is used to confirm the effectiveness of the proposed antenna as a lens integrated feed. WIPL-D, a method of moment-based commercial three-dimensional EM ***[AUTHOR: Electromagnetic?]*** solver,[1] is used for antenna design and optimization.

The main focus of this letter is on the printed feed design and concept validation. The design of shaped lenses for broadband operation is out of the scope of this letter and will be presented elsewhere. Likewise, optimization and characterization of the integrated mixer or intermediate frequency (IF) circuit are out of scope.

II. Antenna Basic Configuration

The proposed antenna layout is presented in Fig. 1(a). It is based on the exponentially tapered slot concept (ETS) studied by simulation in [4], here modified into a crossed slot arrangement with an intersecting square slot. Unlike in [4], here a finite diameter D of metallization is considered. The feeding of the antenna is done at the center of the slots between two opposing inner “petals,” thus defining the E-plane. The reasoning for using two slots in a crossed configuration (instead of one as in [4]) is that this improves similarity between E- and H-plane radiation patterns. The crossed exponential slots alone produce a reasonably broad bandwidth impedance characteristic, on the order of 50%; the square slot adds an extra resonance at higher frequencies, thus enlarging further the whole bandwidth. Hereafter we refer to this antenna as XETS for brevity. Its perfect symmetry with respect to the feed plane (passing through the diode and the petals vertex) ensures that the resulting E-filed presents quite pure linear polarization along this plane irrespective of frequency.

If required, the XETS design can be adjusted to accommodate a replica of two of the inner petals of the antenna at the backside of the substrate [Fig. 1(b)]. The receiver can then be mounted

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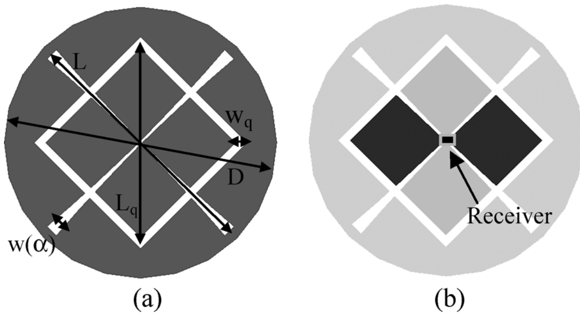

Fig. 1. Antenna layout: (a) front face and (b) optional back face.

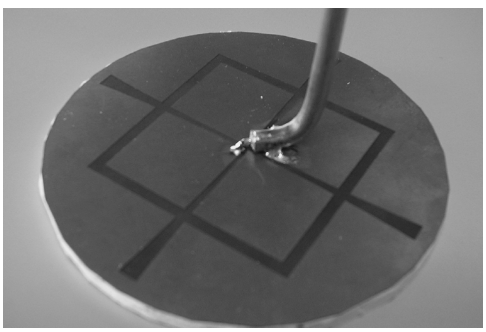

Fig. 2. Standalone XETS prototype for 1.4–5 GHz.

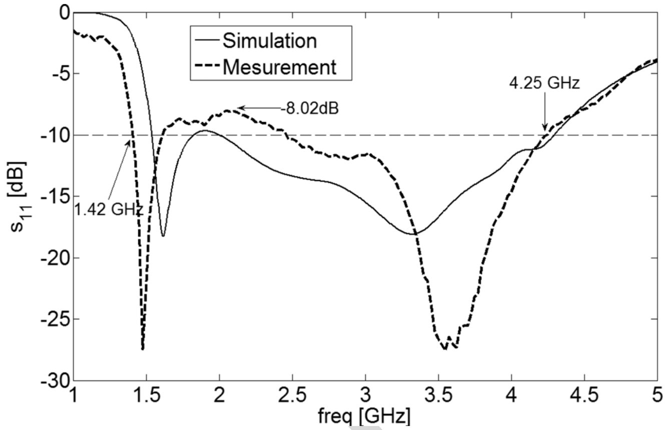

Fig. 3. Standalone XETS input reflection coefficient.

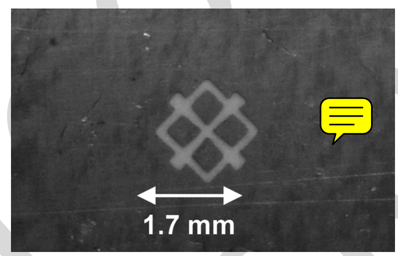

Fig. 4. Photo of the front face of the XETS prototype for 30–70 GHz operation for integration with a MACOR lens.

across these back petals, which couple capacitively at radio frequency (RF) with the corresponding front petals of the antenna. This configuration has the advantage that the front face of the feed can be fixed in perfect contact with the lens base (without the interposition of the substrate) while the receiver and mixing circuit at the back of the substrate are easily accessed without the need for vias. Furthermore, it was experimentally verified that if an alternative classical RLC diode detector configuration [5] is used, these petals act as the needed (parallel plate) capacitor.

The slot exponential geometry is given by

$$w(\alpha) = w_0 \mathrm{e}^{\frac{\alpha}{C_0}} \quad (1)$$

where w is the slot width and α is the slot longitudinal coordinate measured from the center of the slot, extending up to $\alpha = L/2$, the slot half-length. Slot width at the center is w_0 and C_0 is the exponential expansion parameter. The intersecting square slot has mid-diagonal L_q and diagonal slot width w_q. The geometry is thus defined by a total of five design parameters.

III. Standalone XETS Antenna

As explained, an XETS antenna radiating directly into air serves the purpose of easily testing the concept and validating the simulation model. The antenna is printed on a single side of a 10 mil Duroid 5880 substrate with $\varepsilon_r = 2.2$, $\tan(\delta) = 0.0012$ using the single-face XETS approach of Fig. 1(a). Therefore, in this example, the backside of the substrate does not have a metallization. A 50 Ω coaxial cable (EZ-141) is soldered between two opposing petals; see Fig. 2. The same coaxial cable feeding configuration is used in the simulations.

After optimization for the 1.5–4 GHz band, the slots came with total length $L = 64.62$ mm, center width $w_0 = 0.618$ mm, $C_0 = 19$, square slot diagonal $L_\mathrm{q} = 51.81$ mm, and diagonal width $w_\mathrm{q} = 3$ mm. The metallization was chopped at a diameter $D = 70$ mm (0.33λ at the lower edge of the band).

The measured input reflection coefficient of the standalone XETS prototype is presented in Fig. 3, compared to simulations. It can be seen that about 2.8 GHz operation bandwidth is obtained, corresponding approximately to 100%. Differences between simulated results and measurements can be attributed to the influence of the coaxial cable and its connection to the petals of the antenna. Nevertheless, this prototype allows demonstrating the impedance broadband properties of the XETS and validating the simulation model. For conciseness, radiation pattern characteristics are addressed only for the second prototype, but it is mentioned anyway that 97% radiation efficiency is estimated from calculated radiation patterns.

IV. XETS for Lens Integration

A. XETS Design and Characterization

This second prototype is designed and manufactured to be integrated with a MACOR elliptical lens for operation between 35 and 70 GHz. MACOR complex permittivity was measured at 40 and 60 GHz bands using both a standard waveguide method and the open Fabry–Perot resonator method, producing an almost constant value of $\varepsilon_\mathrm{r} = 5.6$, $\tan\delta = 0.012$. The double-face XETS configuration is adopted for this prototype. The same 10 mil Duroid 5880 substrate is used, but instead of the coaxial cable a zero-biased Schottky diode (Agilent HSCH-9161 [5]) is connected between the two backface petals [Fig. 1(b)]. This allows measuring the lens radiation pattern using the diode as a mixer, as will be explained ahead.

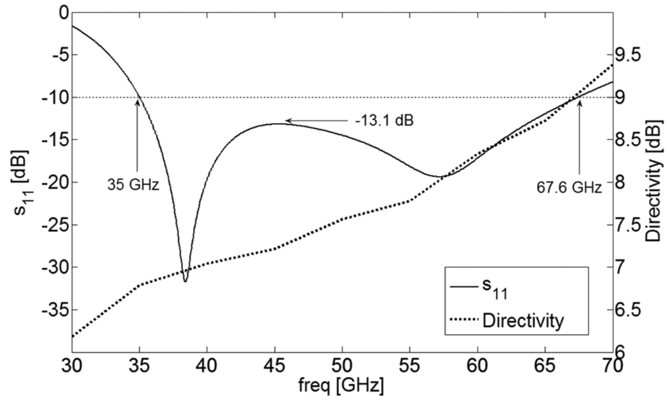

Fig. 5. Simulated input reflection coefficient and directivity.

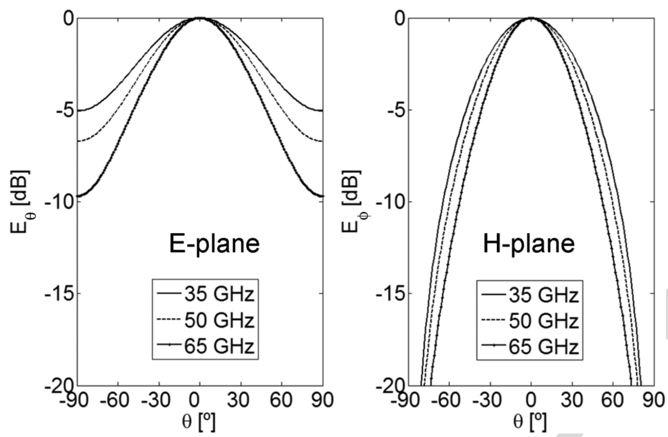

Fig. 6. Simulated XETS radiation patterns.

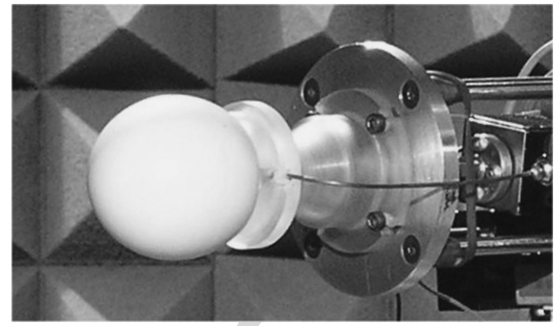

Fig. 7. Fabricated MACOR elliptical lens.

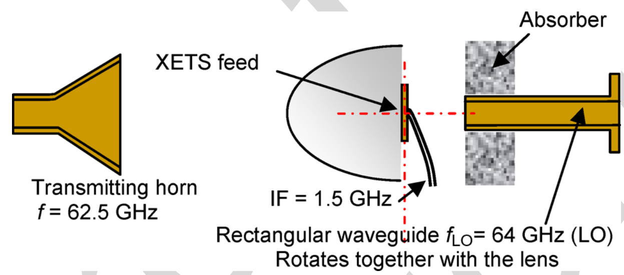

Fig. 8. Radiation pattern measurement setup.

This XETS antenna is designed considering that the top face of the dielectric is radiating into MACOR half-space and the backface into air half-space. The high permittivity of the MACOR ensures that the antenna mainly radiates into MACOR, which is the usual approach with slots or with other single metal layer feeds used with integrated lenses [1].

After optimization, the obtained XETS dimensions are $L = 1.7$ mm, $w_0 = 0.0872$ mm, $C_0 = 0.766$, $L_q = 1.7$ mm, and $w_q = 0.15$ mm (Fig. 4). The impedance at the feeding points of the back petals was designed to match 50 Ω which is approximately the RF impedance of the used Schottky diode. The simulated XETS input reflection coefficient at these feeding points is presented in Fig. 5. Assuming the previously stated XETS design conditions, Duroid substrate permittivity was assumed constant over the band [6]. Nominal values were considered for Duroid loss tangent and for metal losses. Fig. 5 shows the same type of broadband s_{11} frequency behavior as in Fig. 2. The simulated radiation pattern of the XETS is presented in Fig. 6 for 35, 50, and 65 GHz when radiating into MACOR half-space. It is seen that the E-plane radiation pattern is broader and more sensitive to frequency than the H-plane. Nevertheless, it is far narrower than for the single ETS of

The XETS directivity versus frequency when radiating into MACOR half-space is superimposed on Fig. 5 showing that the directivity increases linearly by about 3 dB within the frequency band of design. It is noted that this linear increase in directivity may be useful for collimated lens feeding since it counteracts the lens inherent aperture frequency dependence by decreasing the lens illuminated area with increasing frequency. The study of this compensation effect is beyond the scope of this letter and will be addressed elsewhere.

Simulations also have shown that the above XETS radiation efficiency ranges from 88% at 40 GHz to 95% at 70 GHz. This is calculated from the ratio of power radiated into MACOR half-space to the power at the XETS feeding port and takes into account Duroid material losses as well as metal losses.

B. Integration With the Lens

A MACOR elliptic lens with minor radius $a = 25$ mm and major radius $b = 27.64$ mm has been manufactured; see Fig. 7. The previous XETS feed was attached directly to the base of the lens, with the previously referred Schottky diode used as the mixing element.

The radiation pattern measurement setup is shown schematically in Fig. 8. The lens under test is illuminated by the far field of a transmitting horn at the TX frequency. The local oscillator (LO) signal is fed to the lens through its rear side, using the open end of a rectangular waveguide.

In this way the Schottky diode receives both the Tx signal (through the lens) and the LO signal (through the air from the back), producing the desired IF signal. The LO assembly is fixed with respect to the lens, so that the LO signal amplitude illuminating the XETS does not change with lens rotation, whereas the IF signal amplitude changes only in response to lens radiation pattern at the TX frequency. The IF signal is preamplified and conveyed onto a spectrum analyzer for amplitude logging versus azimuth rotation.

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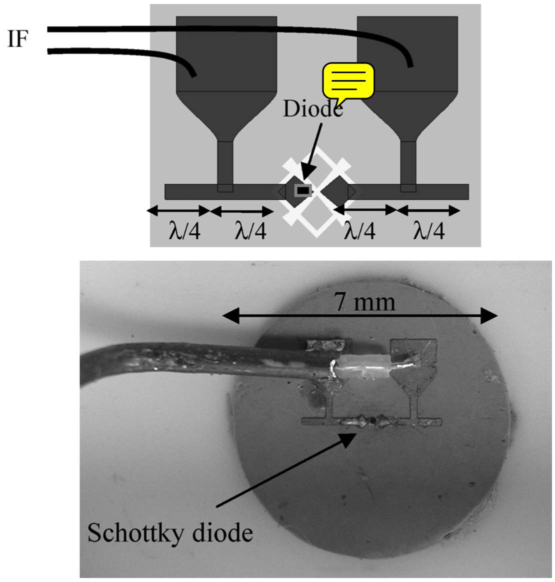

Fig. 9. Antenna back-face layout with IF retrieving circuit. (a) Schematic and (b) prototype photo.

retrieving circuit is out of the scope of this letter. Just to prove the XETS concept, a basic IF retrieving circuit is added at the back face of the XETS, where it has less influence on its radiation pattern. The IF signal is picked at the outer edges of the back petals through microstrip lines using the XETS front-face metallization as the microstrip ground plane. In order to ensure that the IF circuit does not change the XETS s_{11} at RF, a $\lambda/4$ open stub is used as shown in Fig. 9 so that the microstrip presents high impedance at the edge of the petals at RF.

Although the presented IF circuit configuration is narrow band, it was found after optimization that the circuit also allowed good power transfer at an additional higher RF frequency, thus enabling testing the XETS/lens assembly at two well-separated frequencies. The IF retrieving circuit was designed for operation at 43 GHz with an IF of 1.5 GHz. The additional operating frequency obtained by the same circuit is at 61 GHz, with the same 1.5 GHz IF value.

Before measuring the radiation pattern, a system amplitude calibration was performed by positioning the lens antenna assembly at the maximum radiation direction and then sweeping the power amplitude of the transmitting (TX) horn. Maximum used TX power was +13 dBm, with 20 dBi TX horn gain, +13 dBm LO power, 10 mm distance from LO waveguide open-end to the back of the XETS, and 1.65 m measurement distance. Almost 45 dB dynamic range with linear characteristic was obtained, both at 43 and 61 GHz.

Measured radiation patterns are presented in Fig. 10 for the E- and the H-plane at both frequencies. It shows the expected typical radiation pattern of the elliptical lens. As could be anticipated from Fig. 6, E-plane radiation pattern is narrower, with higher side-lobe level than the H-plane. Cross-polar level at 43 GHz is below −27 dB in the E-plane and −35 dB in the H-plane. The increase in cross-polar level for 61 GHz is partly explained by a small misalignment between front and back metallization of the fabricated XETS prototype. Simulations confirmed that such misalignment degrades cross-polarization as

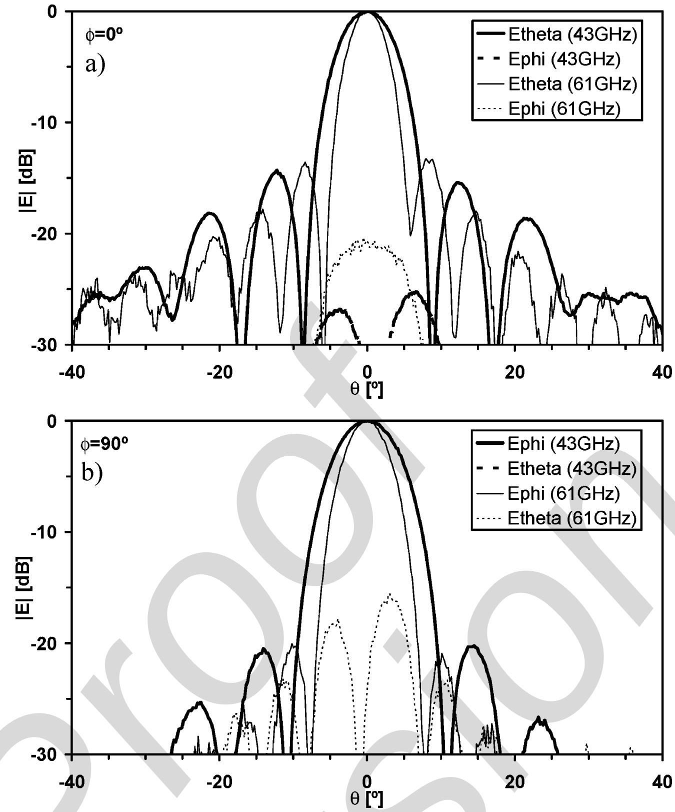

Fig. 10. Measured elliptical lens radiation patterns fed by XETS. (a) E-plane and (b) H-plane.

frequency increases. Even so, measured cross-polarization at 61 GHz is below −20 dB in the E-plane and −15 dB in the H-plane, which is better than can be obtained with a self-complimentary log-periodic feed.

V. Conclusions

This letter presents a new linearly polarized broadband printed antenna configuration that can be used either for standalone antenna or as an integrated feed for millimeter-wave or submillimeter-wave lens applications.

Its main features are compactness, broadband return loss characteristic, pure and stable linear polarization versus frequency, and very convenient configuration for integration of active devices allowing full XETS contact with the dielectric lens base without interposition of the substrate. Although a narrow-band IF retrieving circuit was adopted for the lens integrated example, the broadband characteristic was illustrated by measurements at two well-separated frequencies. In addition, the standalone prototype confirmed the potential bandwidth of the XETS.

Additional simulations performed for two H-plane contiguous XETS antennas, with center separation of 2 mm, produced isolation better than 18 dB across the bandwidth from 35 to 70 GHz. This is another added value of the XETS feed for multiple-beam lens applications. The XETS has been tested with success also for other integrated lens antenna configurations.

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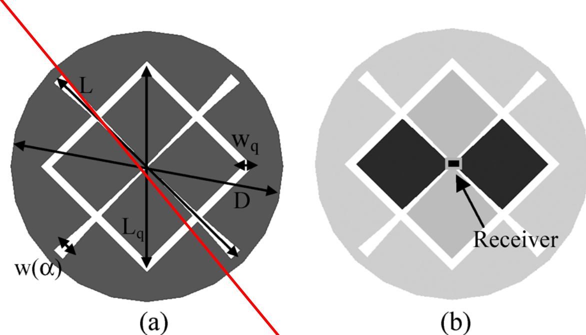
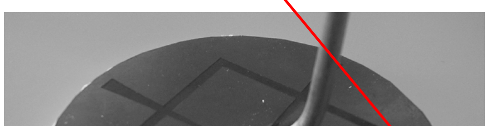


Fig. 1. Antenna layout: (a) front face and (b) optional back face.



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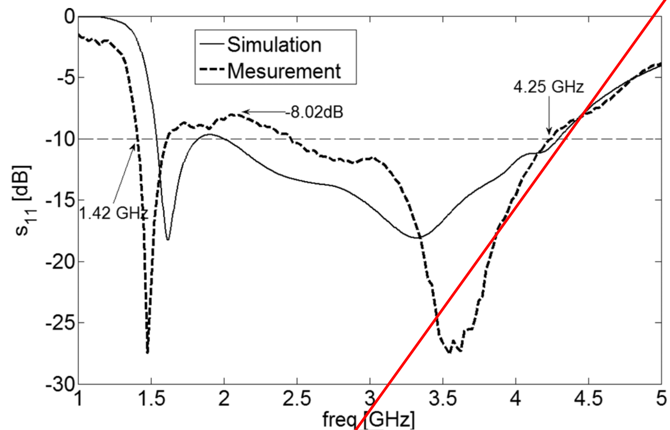

Fig. 3. Standalone XETS input reflection coefficient.

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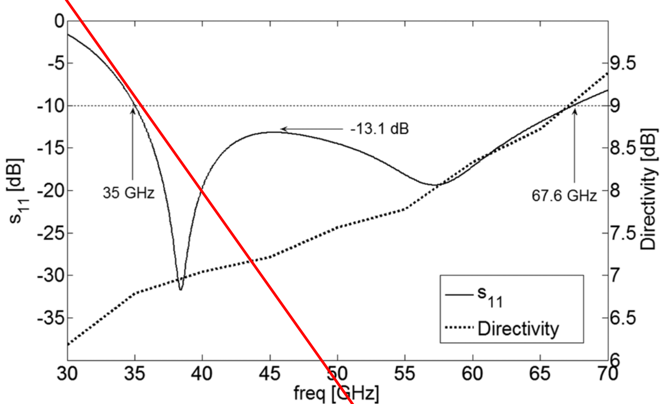
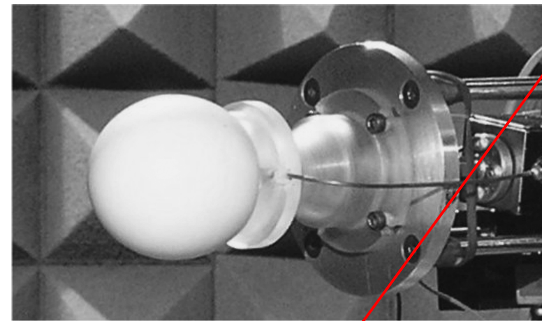


Fig. 5. Simulated input reflection coefficient and directivity.



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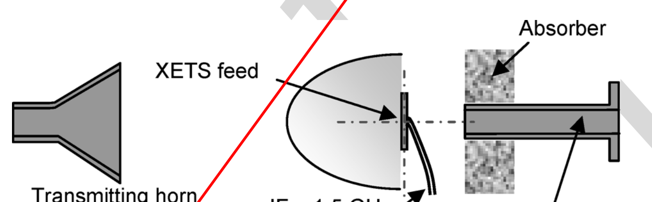

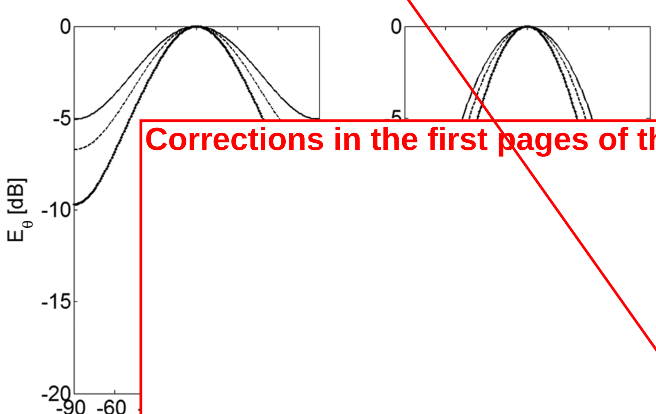

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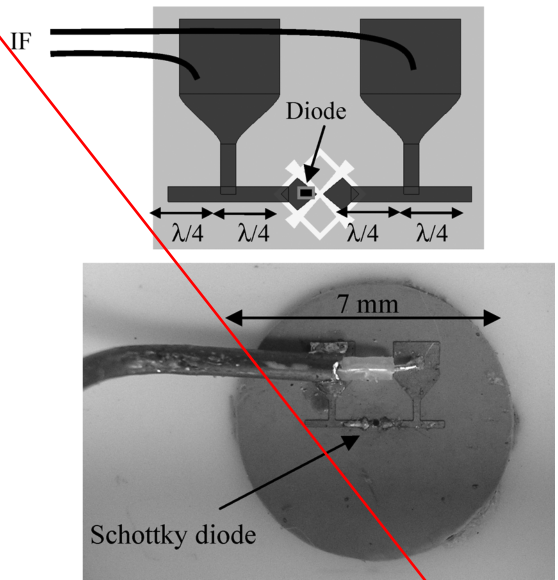
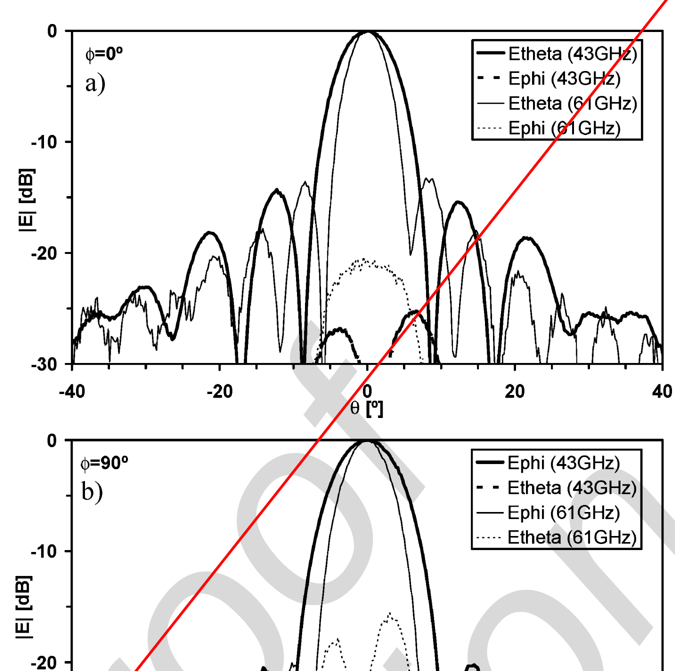


Fig. 9. Antenna back-face layout with IF retrieving circuit. (a) Schematic and (b) prototype photo.



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used TX power was +13 dBm, with 20 dBi TX horn gain, +13 dBm LO power, 10 mm distance from LO waveguide open-end to the back of the XETS, and 1.65 m measurement distance. Almost 45 dB dynamic range with linear characteristic was obtained, both at 43 and 61 GHz.

Measured radiation patterns are presented in Fig. 10 for the E- and the H-plane at both frequencies. It shows the expected typical radiation pattern of the elliptical lens. As could be anticipated from Fig. 6, E-plane radiation pattern is narrower, with higher side-lobe level than the H-plane. Cross-polar level at 43 GHz is below -27 dB in the E-plane and -35 dB in the H-plane. The increase in cross-polar level for 61 GHz is partly explained by a small misalignment between front and back metallization of the fabricated XETS prototype. Simulations confirmed that such misalignment degrades cross-polarization as

quency, and very convenient configuration for integration of active devices allowing full XETS contact with the dielectric lens base without interposition of the substrate. Although a narrow-band IF retrieving circuit was adopted for the lens integrated example, the broadband characteristic was illustrated by measurements at two well-separated frequencies. In addition, the standalone prototype confirmed the potential bandwidth of the XETS.

Additional simulations performed for two H-plane contiguous XETS antennas, with center separation of 2 mm, produced isolation better than 18 dB across the bandwidth from 35 to 70 GHz. This is another added value of the XETS feed for multiple-beam lens applications. The XETS has been tested with success also for other integrated lens antenna configurations.

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Corrections in the first pages of this pdf.