UWB, Non Dispersive Radiation from the Planarly Fed Leaky Lens Antenna. Part II: Demonstrators and Measurements

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Abstract—We provide for the first time the experimental characterization of a planarly fed ultra-wideband leaky lens antenna. The paper includes the description and the experimental characterization of two antenna prototypes with radiating element realized in printed circuit board technology. The impedance parameters and the radiation patterns of the antennas have been measured showing excellent pattern quality and efficiency. The link between two antennas has also been characterized in the frequency and time domains in terms of mutual coupling impulse response respectively. Unprecedented performance in terms of pulse fidelity are demonstrated suggesting very high potentials of these antennas for all applications that require preservation of narrow pulses.

I. INTRODUCTION

For most radar and communication applications that require a wide frequency bandwidth the linearity of the phase of the antenna transfer function is of great importance. If the antenna is dispersive (i.e. the phase does not vary linearly with frequency) compensations at system level must be included, such as sub-divisions of the bands, digital signal processing, inclusions of filters, etc. [1]. The most linear phase responses are associated to antennas derived from TEM-like horns. For instance the Vivaldi antenna, which is a low cost implementation of TEM horns, is a very successful example, see [2]. However, it is well known that its phase center moves along the longitudinal axis. This implies that the phase linearity is only limited to the broadside direction.

The stability of the phase center as a function of the frequency is only a necessary condition for the linearity of the phase in all observation directions. The most successful wideband antennas that present fixed phase centers are often derived from spirals or from the log periodic concept. As an example, the Eleven antenna [3] has recently been proposed for decade Bandwidth (BW) reflector’s excitation. However, as shown in [2] the log periodic concept is intrinsically associated to a non linear phase variation of the transfer function. The same applies for spirals. Overall, it appears that no antennas are presently known capable of radiating non dispersively over the entire main beam and over very large bandwidths.

When the attention is shifted from a single antenna to a radiated link, the linearity of the phase of the antenna transfer function is not sufficient for the reception of a non distorted replica of the input impulse. Also the amplitude of the spectrum of the transmitted impulse must be preserved.

The planarly fed Leaky Lens antenna, described in paper [4], appears to be well performing with respect to both dispersion and amplitude distortion. In [4], the concept and design of the antenna was presented. In this paper, corresponding hardware prototypes are described and experimentally characterized. To demonstrate the ultra-wide bandwidth performance while retaining manageable lens dimensions, 12 GHz has been chosen as lowest operating frequency. The planar feed has been realized in standard printed circuit board (PCB) technology. Both types of antennas discussed in [4], with and without matching layers, have been manufactured. The matching layers reduce the reflection at the dielectric/air interface and this is therefore the preferred implementation of the Leaky Lens antenna design. However, for applications at sub-mm wave frequencies the realization of the matching layers poses serious technological challenges. Thus, the performance degradation of the planarly fed Leaky Lens antenna without the matching layers has also been quantified.

A link between two prototypes has been experimentally characterized. From the measured S-parameters, the pulse preserving property of the antenna link demonstrates the phase linearity and phase center stability of each antenna as well as the spectral amplitude preservation of the link. While the phase preserving properties arise from the Enhanced Leaky Lens radiation mechanism [4], the spectral amplitude preservation is strictly related to the specific geometry chosen for the dielectric lens.

The paper is structured as follows. After a short description of the prototypes in Sec. II, Sec. III presents the S-parameter measurement results for both structures, with and without matching layers, covering the band from 5 to 70 GHz. Sec. IV describes the impulse response of the links between two antennas. Time gating is applied to this response in Sec. V to highlight the dominant wave phenomena characterizing the links. The measured antenna radiation patterns are plotted in Sect. VI for the frequency range 33-75 GHz. Considerations on the results are provided in Sec. VII.

II. PROTOTYPE DESCRIPTION

A 3D radar imaging system operating with 30 GHz bandwidth is currently being designed at TNO. In the frame of this project, a planarly fed Leaky Lens antenna will be integrated on the printed circuit board where the TX/RX frontend circuitry will be hosted. As preliminary step, two prototypes of the antenna have been designed and manufactured to characterize the antenna performance independently from the rest of the system. According to the design guidelines presented in [4] the prototypes have been manufactured to operate efficiently as transmitter and receiver in the frequency band 30 to 60 GHz. The dielectric lens has been made of a
material for microwave applications \( \epsilon_r = 9.8, \tan\delta = 0.002 \) that is commercially available in cylindrical rods of up to 100mm of diameter. The material could be machined at TNO workshop with sufficient accuracy. The relevant dimensions of the lens and of the feeding structure in the PCB can be found in [4] and will not be repeated here for the sake of brevity. Fig. 1 shows the lateral and top view of one of the prototypes. In Fig. 1(a) the holder consisting of a thick metal plate (1mm) is also visible on top of a plastic block that was introduced to provide support to the antenna PCB. Because of the high front-to-back ratio of the planarly fed Leaky Lens antenna, this structure does not significantly affect the radiation performance. A slab of foam material, \( \epsilon \approx 1 \), was inserted to maintain a constant separation between the lens and the ground plane where the slot is etched and ensure the enhanced radiation mechanism. The micro-strip extends at the side of the lens, where it is fed through a Mini-SMP coaxial cable connector. To protect the mini-SMP, 1.85mm connector safers are used. As outlined in [4], to match the 80\( \Omega \) antenna impedance to the 50\( \Omega \) impedance of the connector the micro-strip width has accordingly been tapered from 200\( \mu \)m to 300\( \mu \)m. The overall distance between the coaxial connector and the center of the slot is about 1cm.

After measuring the performance of the two antenna prototypes, two sets of curved matching layers conformal to the original lens have been milled away from three dielectric roads of nominal permittivity \( \epsilon_r = 6.5, 3.5, 2.5 \) and \( \tan\delta = 0.002 \). The details of the stratification were described in Sec. IV-A.3 of [4]. The matching layers have then been glued to each other and to the lens of the original antennas and new measurements have been carried out.

III. Scattering Parameters

The antenna scattering parameters have been measured using an Agilent vector network analyzer, which is able to perform measurements up to 70 GHz. The reflection behavior of each antenna has been investigated in terms of S11. The performance of the two manufactured antennas will be shown in Fig. 3.

The transmit-receive antenna link has been characterized in terms of S12 with the measurement set up depicted in Fig. 2. The antennas were placed at about 20cm distance, measured between the two micro-strip-slot transitions. The antenna alignment was optimized to provide maximum mutual coupling.

The antenna scattering parameters will be discussed separately for the implementation without matching layers and with matching layers.

A. Without Matching Layers

The measured scattering parameters of the two antennas, S11 and S22, are shown in Fig. 3(a) and (b) respectively. The measurements were performed with the same setup used to characterize the antenna link in Fig. 2. However, since the distance between the two antennas is relatively large and the S12 is in the order of -23 dB, it is believed that the SII parameters provide a very good approximation of the reflection coefficient for each one of the two antennas in isolation. The amplitudes of all SII parameters are plotted in dB’s as a function of the frequency in the range 5-70 GHz. The resolution obtained with this frequency range is so high, that the location of the strongest reflection could easily be identified by performing the Inverse Fourier transform (IFT) of the frequency domain data and observing the time domain data. This reflection was, as expected, associated to the connector-microstrip transition. Accordingly, it has been possible to gate out this transition...
effect to characterize the matching of the two antennas without
the effect of the connector. Fig. 3(a) and (b) present also the
results pertinent to this gated situation (continuous line).

Fig. 3. Measured Sii parameters for antennas (1) in a) and (2) in b) without
matching layers, dashed lines. For both antennas also the results pertinent
to the case in which the reflections at the connectors are gated out are included,
continuous lines.

The curves obtained after time gating show very good
matching performance for both antennas with SII lower than
-10 dB from 15 GHz on. The rapid oscillation as a function
of the frequency can be associated to reflections inside the
dielectric lenses. Simulations performed with the commercial
FDTD-based software package CST Microwave Studio [5],
not reported for brevity, are in excellent agreement with these
measured results. The simulations actually indicate that this
same structure should remain matched with SII better than -15
dB up to at least 100 GHz (the increase of the computational
burden did not allow performing the simulations for higher
frequencies). When the connector effect is considered, the
matching deteriorates significantly: the oscillations in the SII
parameters can be tracked to standing waves between the slot
and the connector. Notably, the impact of the connectors differs
significantly in the two antennas. Being the designs exactly the
same it is apparent that the soldering of the coaxial connector
to the PCB is the most unreliable part of this antenna design.
However, the use of such connector will not be necessary in
the final integrated design.

In Fig. 4 the amplitude of the measured S12 is plotted as a
function of the frequency.

The S12 parameter presents significant oscillations due to
the reflections inside the lens and due to the mismatch associ-
ated to the transition from coaxial cable to µstrip. Moreover
the S12 is impacted by the ohmic losses due to the µstrip lines
lengths and by the ohmic losses in the dielectric composing
the lenses.

Fig. 4. Measured S12 parameter for antennas (1) and (2) without matching
layers.

Estimated Efficiency Without Matching Layers

The causes of reduced efficiency for the antenna prototypes
without matching layers can be identified and quantified by
means of measurements and simulations:

- Ohmic losses in the dielectric lens, varying from 0.5 dB
  at 20 GHz to 1.5 dB at 70 GHz (calculated using
the nominal value of the loss provided by the material
manufacturer);
- Mismatch losses at the connector, measured with the Sii
  parameters;
- Ohmic losses in the µstrip line, varying from 0.5 dB
  at 20 GHz to 1.5 dB at 70 GHz (calculated using the
  nominal value of the loss in the dielectric as provided by
  the manufacturer).

These losses, partly calculated and partly measured, are
summarized in Fig. 5, which shows the estimated efficiency
of antenna (1).

It should be noted that the antennas eventually will be used
without µstrips and connectors.

B. With Matching Layers

The two antenna prototypes equipped with matching layers
have then been characterized. The S11 parameter of antenna
(1) is shown in Fig. 6. In this case only the curve pertinent to
the situation in which the connectors are gated out is presented.

Also in this case excellent matching performance with S11
lower than -10 dB from 12 GHz on is observed. The rapid
oscillation as a function of the frequency is significantly reduced in amplitude with respect to the corresponding case in absence of matching layers. Again simulations performed with CST, not reported for brevity, are in very good agreement with these measured results.

Fig. 7 shows the amplitude of the measured S12 as a function of the frequency. In the whole frequency range the S12 is at least 5 dB higher than the value obtained without matching layers. Moreover, the oscillations are now much weaker, with the S12 amplitude varying in a 7 dB band (-15 dB to -22 dB) from 15 to 70 GHz.

Estimated Efficiency With Matching Layers

Based on the comparison between measurements with and without matching layers, one can clearly establish that the presence of matching layers ensures an increase in gain of the order of 2-3 dB per antenna. This does not imply a much higher efficiency of the antenna in terms of losses. The ohmic losses and the losses due to mismatch at the connector are for these antennas essentially the same as those discussed for the case of no matching layers. However, an increase of 2 dB in the transmission efficiency at the dielectric-air interface implies that the radiation pattern is better behaved in the sense that more power is radiated into the main beam rather than in the side lobes. This will be explicitly shown in Sec. VI.

IV. TIME DOMAIN FROM FREQUENCY DOMAIN

The link between a transmitting and a receiving antenna can be characterized in terms of its complex transfer function

$$H(f) = U_{RX}(\omega)/U_{TX}(\omega),$$

where $U_{RX}(\omega)$ and $U_{TX}(\omega)$ are the spectra of the received and transmitted voltages. The coupling parameter in the frequency domain, $S_{12}(\omega)$, is linked to the complex transfer function of the antennas involved in the link by [2]:

$$S_{21}(\omega) = H_{TX}(\omega)H_{RX}(\omega)\frac{j\omega}{2\pi rc}e^{-j\omega r/c},$$

where $H_{TX}(\omega)$ and $H_{RX}(\omega)$ are the transfer functions of transmit and receive antenna and $r$ is distance between these antennas. In this section the impulse response of the link $S_{12}(t)$ is derived over a 65 GHz BW, from 5 to 70 GHz, by means of the IFT of the measured $S_{12}(\omega)$.

A parameter frequently used to quantify the pulse distortion is the fidelity factor. It is in general defined with respect to a predefined reference signal [6], [7]:

$$F = \max[\frac{\int_{-\infty}^{\infty} s_{ref}(t)s_{12}(t-\tau)d\tau}{\int_{-\infty}^{\infty} |s_{ref}(\tau)|^2d\tau \int_{-\infty}^{\infty} |s_{12}(\tau)|^2d\tau}].$$

In the following, the reference signal $s_{ref}(t)$ will be a sinc associated to the mentioned 65 GHz band, which can be expressed as

$$s_{ref}(t) = FT^{-1}[S_{ref}(\omega)] = \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} e^{-j\omega t}d\omega$$

where $\omega_1 = 2\pi5GHz$ and $\omega_2 = 2\pi70GHz$. 

A. With Matching Layers

Fig. 8 shows the time domain representation, normalized to the maximum, of the amplitude of the S12 parameter measured with the setup in Fig. 2 for the case in which the lenses are covered by matching layers.

The main peak of the signal arrives at the receiver after approximately 1.35 ns corresponding to 404 mm of equivalent free space propagation. This propagation time can be explained accounting for 1.4cm of free-space propagation plus 6.4cm of propagation in the two lenses (equivalent to 18.5cm in free space) and 8cm of micro- strip and coaxial cables propagation. A second peak of amplitude 22 dB smaller than the first peak appears 0.3ns after this, corresponding to approximately 9.2cm of free space propagation. It can be associated to single reflections inside the lens, as highlighted in the inset of the figure. This effect could be considered as a measure of the ringing. If as reference for defining the ringing an amplitude of -13dB for the secondary peak is considered, also in this respect the leaky lens antenna outperforms the Vivaldi and the log-periodic antennas reported in [2]. Since there are no other important images arriving at later times, the statement in Sec. IV.A.2 of [4] that the planarly fed leaky lens antenna does not support double reflections inside the lens thanks to its directive pattern is fully validated.

![Fig. 8. Normalized time domain representation of the S12 parameter for the antennas with matching layers.](image)

A comparison between the response of the antenna link in time domain and the reference signal, delayed of 1.35ns, to present the maximum in correspondence of the main peak of the link impulse response is shown in Fig. 9. Note that the scale is expanded with respect to that in Fig. 8. The curves show impressive similarity and one can observe that the half power width of the measured pulse is only 0.002 ns longer than that of the reference signal (0.015ns instead of 0.013 ns). To more rigorously quantify the pulse distortion introduced by the combined antennas the fidelity factor has been calculated. For the entire measured band (\(\omega_1 = 2\pi 5GHz\), and \(\omega_2 = 2\pi 70GHz\)) the fidelity factor of the link between two leaky lenses with matching layers is 0.94. To the best of our knowledge such a high fidelity factor on a frequency BW 1:14, leaky lenses with matching layers is 0.94. To the best of our

When one considers only the frequencies above the threshold of 15 GHz, after which the matching layers start to function, (see Sec. IV of [4]), the fidelity factors becomes 0.97, as visible in Fig. 10. The frequency band with fidelity higher than 0.97 is in fact 1:5. Note that comparable performance in terms of fidelity have been shown by Vivaldi antennas on BW in the order of 1:3 [7], but only in the broadside direction.

At the time of writing this paper, TNO measurement set up did not allow us to perform S-parameter measurements at frequencies higher than 70 GHz. However it can be observed that the S12 starts decreasing in the higher portion of the band due to increase in the losses. Nevertheless simulations carried out using CST Microwave Studio have shown that one can obtain, in relative BW higher than 1:7, the fidelity factor larger than 0.97.

Phase Center Stability With Matching Layers

As explained in Sec. V of [4], the excellent dispersivity properties that were presented in the previous Figures are due to both the linear growth of the gain and the linear variation of the phase of the received signal as a function of the frequency. While the gain can be derived from the amplitude of the S12(\(\omega\)), the phase variation over a certain frequency band can be read from the position of the peak of the link impulse response. Fig. 11 shows on the right scale the distance between the two antennas composing the link as derived from the position of the peak of the received signal in time domain over different frequency bands. Thus, for instance, performing the IFT of S12(\(\omega\)) by only retaining the frequency components from 5 to 21 GHz, one would observe that the peak of the received signal would arrive at a moment which corresponds to 402.5 mm of propagation in free space. Similarly performing
the phase center does not move with frequency. Considering that the slot width is 0.5 mm, one can readily observe that the corresponding variation of the phase center in each of the antennas is less than ±0.32 mm. Considering that the slot width is 0.5 mm, one can state that the phase center does not move with frequency.

This experimental demonstration only holds for broadside links. However, since the antenna behaves accordingly to the dominant ray picture provided in Fig. 12 of Sect. V of [4], the phase center stability can be implied for at least the entire main beam. Note that this antenna is the only one, to our knowledge, which is at the same time efficient, weakly dispersive and with stable phase center. Uniting this property with the intrinsic directivity, one can use the leaky lenses to excite a reflector with high F/D, maintaining the low dispersivity. Accordingly a focal plane arrangement, can be used to generate multiple secondary beams, hundreds, without significant off-focus degradation. This was not possible until now, with any other feed.

The time domain link impulse response in the absence of matching layers is discussed in Appendix A.

V. FREQUENCY DOMAIN FROM TIME DOMAIN

The investigation of the time domain representation of the S12 parameter allows one to identify the critical time domain zones in which the dominant wave mechanisms can be recognized. Fig. 12 shows a zoomed time window in which most of the S12 signal is concentrated. The two curves correspond to the links including antennas with (solid line) and without (dashed line) matching layers. Note that here the amplitudes of the $S_{12}(t)$ are normalized to the maximum of the signal in the presence of matching layers, to fully appreciate the relative difference between the two signal intensities and qualities. It is apparent that for both links the bulk portion of the signal arrives to the receiver between 1.3 and 1.4 ns. Also it is relatively simple to identify the zone between 1.6 and 1.7 ns as the window where contributions arrive to the receiver after having undergone a single reflection at the dielectric-air interface and on the ground plane. Finally we can associate the zone between 1.4 and 1.6 ns as the zone where further contributions associated to multiple reflections inside the lens or between the connector and the slot in antennas (1) and (2) are concentrated.

This subdivision suggests to adopt different gating of the time domain signals to highlight the frequency signature of each contribution.

Fig. 10. Comparison between the measured impulse response of the combined antennas and an ideal 55 GHz bandwidth (15-70 GHz) delayed pulse.

Fig. 11. On the right scale: optimal delay that should be introduced to recover 16 GHz BW pulses centered at different frequencies. On the left scale: corresponding phase center variation with respect to the average.

Fig. 12. Zoomed time window were most of the link impulse response is concentrated. The responses for both antenna links, with (solid line) and without (dashed line) matching layers are plotted.

Fig. 13 shows the spectral signature of the main peaks of the impulse response for the two antennas. A time gate between 0 and 1.38 ns (window 1) is applied to neglect all contributions following the main peak. It is apparent that the amplitude difference between the links with and without matching layer is essentially spread through the entire frequency range from 5 to 70 GHz. A 6 dB band (-22 to -16 dB with matching layers and -28 to -22 dB without matching layers) extends from 10 to 70 GHz for both links. This is the core graph that highlights the potentials of the leaky lens antenna for low dispersivity as claimed in this series of articles. If ohmic losses were lower the dispersivity would also be lower. In fact one can observe that while the tapering at the beginning of the spectrum is very similar for the links with and without matching layers, the antennas with matching layers are characterized by noticeably higher losses at high frequencies.
With the window 2, the contributions associated to the connectors are included. In Fig. 14, a ripple of intensity 1-2 dB and with approximately 4 GHz period appears for both antenna links, independently from the presence of the matching layers.

When finally the contribution associated to the lens-air interface is introduced (window 3) it appears that the reflections at this interface are essentially insignificant for the antenna with matching layers, Fig. 15. However they are very important for the antenna without matching layers, as they induce 6-8 dB oscillations.

VI. RADIATION PATTERNS MEASUREMENTS

The measurements of the radiation patterns have been performed at the Near Field Antenna Test Range of TNO in the frequency band 33 - 75 GHz. Both co- and cross-polarized components in the $E$ and $H$ planes have been measured for two antennas, one with matching layers and the other without matching layers.

A. Co-polarised Patterns With Matching Layers

The co-polarised radiation patterns in the $E$-plane are shown in Fig. 16 (a) and (b) for the case with matching layers.

The normalized co-polarised radiation patterns in the $H$-plane are plotted in Fig. 17 (a) and (b), with matching layers.
The radiation patterns are circularly symmetric with side lobes below 15 dB on the main planes, except for the H-plane in the higher frequency range. In this case the patterns also appear less symmetric, probably due to an inaccurate alignment of the near field probe with the antenna.

The radiation patterns pertinent to the antennas without matching layers are presented in Appendix B.

B. Gains

The absolute gains of both antennas have been measured as a function of the frequency by comparison with reference standard gain horns. These gains are reported in Fig. 18 for the antennas with and without matching layers. The front-to-back ratio has also been separately measured and it has found to be higher than 25 dB at all frequencies, with and without matching layers. This is also in agreement with predictions from section IV.B.4 of [4].

C. Cross Polarization

The antennas radiate a non negligible amount of power in cross polarization. The exact shape of the patterns is of little significance, but for all antennas with and without matching layers, and for all frequencies, the distribution of the cross polarized fields (according to the third Ludwig definition) is qualitatively described by the schematic drawing shown in the inset of Fig. 19. Four cross-polarized lobes emerge in the diagonal planes. For the case of lenses with matching layers, the maximum level of cross-polarized field with respect to the maximum of the co-polarized field at the same frequency is shown in Fig. 19 as a function of the frequency. The maximum of cross-polarized fields is lower than 9 dB for all frequencies.

VII. CONCLUSIONS

The measurements of the hardware presented in this paper show that the planarly fed UWB Leaky Lens antenna has, over
A link realized using two leaky lens antennas has demonstrated a pulse fidelity $F$ higher than 0.94 (with $F=1$ being the maximum) on the band 5-70 GHz. This pulse fidelity, over the full 3 dB beamwidth and on such a large bandwidth, is much higher than ever reported for any radiated link ($F=0.8$ on a 1-3 BW is often considered excellent). This pulse fidelity is indeed comparable to the one of TEM-guided links at low frequencies, opening a wide range of opportunities for system designers. Since the link is composed of two nominally identical antennas, each of the two antennas essentially radiates non dispersive.

The present Leaky Lens antenna, as it is also directive, can be used as feed for reflector systems capable of operating over decade bandwidths, even if imaging with hundreds of beams is required. Moreover, minor design adaptations can lead to an omnidirectional antenna (only the shape of the lens needs to be changed). This would render the concept suited for short range communications and SAR systems. Finally, the antenna is very inexpensive and simple to manufacture.

APPENDIX A: TIME DOMAIN LINK RESPONSE WITHOUT MATCHING LAYERS

Fig. 20 shows the time domain representation, normalized to the maximum, of the S12 parameter when the two antennas of the link do not include matching layers. The main received signal arrives to the receiver after 1.33 ns corresponding to approximately 399 mm of equivalent free space propagation, (it was 404 mm in the case of the matching layers). The difference corresponds to the matching layers thickness. A second peak can be observed 0.3 ns after the main peak. 0.3 ns approximately correspond to 9 cm in free space and thus to 3 cm in the dielectric. Accordingly, this image can be associated to single reflections in the lens. The amplitude of this second peak is 15 dB lower than the main one. Also in this case the antenna would be indicated as ringing free according to recent indications in the literature [2].

Fig. 21 shows an expanded view of the pulse received and the reference signal, in order to highlight that the pulse is more distorted than in absence of the matching layers (compare to Fig. 9). In particular the pulse is slightly wider and the fidelity factor on the band is $F=0.91$. When the attention is moved to the band 15 to 70 GHz, Fig. 22 the pulse preservation improves significantly and can be quantified by $F=0.96$. Thus the lower portion of the band, suffers most significantly from the pulse dispersion associated to the reflections at the dielectric-air interface.

**Phase Center Stability Without Matching Layers**

Fig. 23 shows on the right scale the distance between the two antennas as measured using different frequency bands, a BW 1:5:

- Directive radiation patterns that are circularly symmetric,
- Low (with respect to other UWB non dispersive antennas) cross-polarisation levels,
- Constant phase center (less than ±0.32 mm variation),
- Efficiency higher than 50% (85% in an integrated system).

The increase of efficiency from 50 % to 85 % in an integrated system is due to the absence of the connectors and $\mu$-strip lines.

The present Leaky Lens antenna, as it is also directive, can be used as feed for reflector systems capable of operating over decade bandwidths, even if imaging with hundreds of beams is required. Moreover, minor design adaptations can lead to an omnidirectional antenna (only the shape of the lens needs to be changed). This would render the concept suited for short range communications and SAR systems. Finally, the antenna is very inexpensive and simple to manufacture.
while the left scale shows the phase center movement. The variation of the phase center in each of the antennas is 0.75 mm, in the lowest band, from 5 to 21 GHz, but then stabilizes to levels comparable to the antenna with matching layers for the higher frequencies. Thus, again it appears that the dispersivity introduced by the absence of matching layers is mostly confined at lower frequencies.

APPENDIX B: RADIATION PATTERNS WITHOUT MATCHING LAYERS

The normalized co-polarized radiation patterns in the $E$-plane are shown in Fig. 24 (a) and (b) for the case without matching layers. The normalised corresponding co-polarised radiation patterns in the $H$-plane are shown in Fig. 25 (a) and (b). Also in this case the patterns are mostly symmetric with respect to broadside. While for low frequencies the patterns are relatively large, the beam width decreases with frequency. The measured side-lobes are lower than -10 dB.

REFERENCES


Fig. 23. On the right scale: optimal delay that should be introduced to recover 16 GHz BW pulses centered at different frequencies. On the left scale: corresponding phase center variation with respect to the average.

Fig. 24. $E$-plane Co-polarized component of the field radiated by the lens without matching layers: a) frequencies 35 to 45 GHz, b) frequencies 50 to 75 GHz.
Fig. 25. $H$-plane Co-polarized component of the field radiated by the lens without matching layers: a) frequencies 35 to 45 GHz, b) frequencies 50 to 75 GHz.