Leaky wave lens antenna for wide/multi band application

Neto, A.; Bruni, S.; Gerini, G.; Sabbadini, M.

Published in:

DOI:
10.1109/EUMC.2005.1610320

Published: 01/01/2005

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the author's version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 27. Nov. 2018
Leaky Wave Lens Antenna for Wide/Multi Band Application

A. Neto\textsuperscript{1}, S. Bruni\textsuperscript{1,2}, G. Gerini\textsuperscript{1}, M. Sabbadini\textsuperscript{3},
\textsuperscript{1}TNO Defence, Security and Safety, Den Haag 2597 AK, The Netherlands. E-mail: andrea.neto, simona.bruni, giampiero.gerini@ tno.nl.
\textsuperscript{2}Department of Information Engineering, University of Siena, 53100, Siena, Italy. E-mail: bruni@dii.unisi.it
\textsuperscript{3}European Space Research and Technology Center (ESTEC), 2200 AG Noordwijk, The Netherlands. E-mail: Marco.Sabbadini@esa.int

Abstract—A novel type of leaky wave antenna is presented. Differently from previously reported leaky wave antennas, it is based on a radiation phenomenon which is intrinsically wide band. The antenna is designed to be an integrated receiver that is compatible with manufacturing technologies in the sub-mm wave ranges. However in order to provide a preliminary proof of concept two scaled models have been designed, manufactured and tested. One is a broad band with operational frequencies between 10 and 20 GHz. The second is dual band operating at 10.5 GHz and 22.5 GHz with 43% and 19% bandwidths. The measurements are in very good agreement with the expectations, demonstrating the potentials of the leaky lens concept to realize integrated transmitters or receivers that are extremely broad band and directive. The ranges of applications are not restricted to sub-mm wave operations for which it was conceived. A joint TNO-ESTEC patent is pending on this type of antennas.

I. INTRODUCTION

Leaky wave antennas have been investigated for a long time [1, and there cited references] and are typically an inexpensive solution for beam scanning antennas. Indeed, since most types of leaky propagation mechanisms are very dispersive, the beam direction can be scanned with frequency, provided one accepts a narrow bandwidth available for each scanning angle. In [2], [3] and [4] the Green’s Function (GF) of a slot printed between two infinite dielectrics, (Fig. 1), has been investigated. This GF is characterized by a leaky-wave type radiation and by very low dispersion. It is intuitive that if a wave propagates at the interface between two different dielectrics, it travels with a phase constant, $\beta$, which is roughly the average of the ones associated to each of the homogeneous media separately. Accordingly, $\beta$ is a slow wave for the less dense medium and a fast wave (leaky) for the denser medium. If the two media are free space and a dense dielectric, radiation occurs in the dielectric. This type of propagation does not involve multiple reflections due to a finite thickness slab, or to a waveguide type of cross section; which typically render dispersive all previously proposed leaky wave radiation mechanisms.

In the frame of an ESA-ESTEC contract, performed together with Satimo and Saab-Ericsson Space, these properties have been explored for the design of two leaky wave antennas: a wide-band antenna and a multi-band antenna. In particular, the design has been tailored to the realization of antennas that could be used as directive feeds for sub-mm wave applications, which is a field where integrated lens antennas are often used [5], [6]. The chosen sub-mm wave environment should not be seen as bounding the ranges of applications, in fact the prototypes manufactured have been scaled to operate in the micro-wave region and their performances are very satisfactory.

II. ANTENNA DESCRIPTION

The slot in Fig. 1, rather than behaving as a transmission line, behaves as a leaky wave antenna. Most of the characteristics of such a structure have been described analytically [2], [3]. For small width ($w_s$) in terms of the wavelength, its properties are dominated by the asymptotic value of the complex propagation constant along the slot

$$k_{x}\textsuperscript{LW} \approx \beta + \frac{k_d^2}{2\beta} \left[ 1 - \frac{j}{\gamma_e} \ln \left( \frac{\gamma_e k_d w_s}{\pi} \right) \right] \quad (1)$$

where $\gamma_e = 1.781...$ is the Euler constant, $k_d = \sqrt{k_s^2 - k_i^2}$, $\beta = \sqrt{k_s^2 + k_i^2}$, $k_i = k_0 / \sqrt{\epsilon_r}$ with $i = 1,2$ and $k_0$ is the free space propagation constant. From the leaky wave propagation constant in (1) one immediately verifies that the phase velocity of the slot varies very little with the frequency since the first order variations as a function of the frequency tends to alter only the imaginary part (attenuation) of the propagation constant. Thus the direction of the main beam is essentially frequency independent. However, it is apparent that the canonical geometry in Fig. 1 is unrealistic for two reasons:

- infinitely long slots do not exist
- infinite homogeneous dielectrics with $\epsilon_{ri} \neq 1$ do not exist.

![Fig. 1. Geometry of the infinitely extended s.e.d. fed slot between two semi-infinite dielectrics.](image-url)
The length of a realizable slot is necessarily finite. However, since the leaky wave that propagates along the slot radiates power in the dielectric, at certain distance from the feed point the amount of power still carried by the wave is negligible. At that point the structure can be terminated without causing significant reflections from the end-point. Accordingly, using (1), it is possible to determine a priori the minimal length of the slot that would not significantly impact the radiation properties of the ideal structure (Fig. 1). The radiation pattern inside the dielectric of the ideal slot structure presents two beams since leaky waves are launched from the feed in the two opposite directions of the slot. In order to obtain a unique beam one can close one of the two arms of the slot line in a short circuit located at $\lambda_e/4$ (being $\lambda_e = \frac{2\pi}{k}$ the effective wavelength in the slot) from the location of the feed.

The second hypothesis, infinite homogeneous dielectrics is crucial to the low dispersion properties of the slot. Indeed most printed leaky structures present strong dispersive properties, which do not allow the slot to operate over a wide band. On the contrary, the ideal slot structure presents two opposite beams regardless of the slot width, in terms of the effective wavelength. The smaller is the slot’s width, the higher is the degree of the leaky mode and the smaller is the effective wavelength. The directivity in the $H$-plane is instead achieved only thanks to the leakage effects. The factor of the leakage is proportional to the frequency, which is an important consideration in the design of the antennas to be excited by two feeds points and operate in two narrower sections not only renders applicable the analysis results pertinent to slots etched between two infinite dielectrics, but also maximizes the directivity in the $E$-plane. The directivity in the $H$-plane is instead achieved only thanks to the leakage effects.

It is interesting to observe that the dielectric lens can be obtained as a portion of a dielectric cone of tip angle $\alpha_t$ (Fig. 2 side view). The portion is obtained by introducing two cutting planes. The first plane (ground plane cut) passes through the tip in such a way that, in the $x$-$z$ plane, the ground plane and the line of the dielectric cone at further distance from the $x$ axis form an angle $\alpha$. The actual value of the angles $\alpha_t$ and $\alpha$ are only functions of the dielectric constant, since $\epsilon_{r1} = 1$

$$\alpha_t = \tan^{-1} \left( \frac{2\sqrt{\epsilon_{r2}/\epsilon_{r1}+1}}{\tan\gamma} \right)$$

where $\alpha = \frac{\pi}{2} - \gamma$ and $\gamma = \cos^{-1} \left( \sqrt{\frac{\epsilon_{r1}+1}{2\epsilon_{r2}}} \right)$.

It is important to note that the use of the elliptical cross sections not only renders applicable the analysis results pertinent to slots etched between two infinite dielectrics, but also maximizes the directivity in the $E$-plane. The directivity in the $H$-plane is instead achieved only thanks to the leakage effects.

In the present long slot case, a ray picture can be associated to the radiation from the slot in the infinite dielectric. This was widely discussed in [3]. Such rays are launched by the slot to form an angle $\gamma$ with the slot axis. $\gamma$ is only function of the dielectric discontinuity ($\epsilon_{r1}$, $\epsilon_{r2}$) and can be expressed by

$$\gamma \approx \cos^{-1} \frac{\epsilon_{r1} + \epsilon_{r2}}{2\epsilon_{r2}} \sqrt{\epsilon_{r1} + \epsilon_{r2}}$$

(2)

By shaping the lens as in Fig. 2, one can obtain that the ray emanating from each point in the slot undergo a double reflection mechanism that simulates the one observed [7] in rotationally symmetric lenses. The shape is obtained as union of an infinite set of cross section planes of elliptical shape and decreasing dimension. The ellipses contain the slot in their lower focus. Fig. 2 explicitly shows the elliptical cross sections and also depicts the rays a) emanating from the slot (lower focus), b) transmitted after the first interface (focus effect in the far field), c) reflected at the first interface, d) transmitted at the second interface (unfocused), e) reflected at the second interface and refocused toward the lower focus. For the sake of convenience the origin of the reference system in Fig. 2 is located in correspondence of the short circuit closer to the feeding point of the slot. This reference system defines the first ellipse cut (see the inset), which actually bounds the maximum dimension of the lens. The choice of cutting the lens in correspondence of the first ellipse cut, minimizes the frequency dependent interference between the leaky rays passing through the bulk of the lens and rays diffracted at the highest point of the first ellipse cut. One can further specify that the rays impinge normally to the dielectric air interface in the $H$-plane (plane parallel to the slot and orthogonal to the ground plane). This characteristic is imposed only for the sake of rendering more intuitive the behavior of the lens maintaining, in the $H$-plane, the beam outside the lens parallel to the rays leaving the slot inside the dielectric.
is the attenuation constant and consequently the higher is the
directivity. Given that the minimal slot’s width, dictated by the
fabrication accuracies of the TNO internal workshop, was 0.1
mm, it was decided to use a 0.2 mm wide slot. This choice
together with a commercially available low loss dielectric
material ($\epsilon_{r2} = 3.27$ from Rogers) guarantees a sufficiently
long slot to obtain the desired directivity and minimize the
reflections at the dielectric air interface. The length of the
slot has been fixed to 120 mm, in order to make acceptable,
also in the X-band, the impact of the reflections occurring
at the far end of the slot. In conclusion, given that the wave
mechanisms in the slot and in the lens are essentially frequency
independent, the basic lens and slot design is a very simple
and straightforward task. The only differences between the
two antennas arise from the feeding arrangements. In both
cases the feeding of the slot is realized via coplanar waveguide
(CPW) lines. For ease of the testing the two realized antenna
prototypes operate at relatively low frequencies and the CPW
lines have been connected to coaxial cable.

III. MEASUREMENT RESULTS

A. Wide Band Antenna

Fig. 3. $S$ parameters for the wide band design operating from 10 to 20 GHz.

![S parameters graph](image)

The wide band antenna has been designed to operate at a
central frequency of 15 GHz. The measured $S_{11}$ parameter,
normalized to 50 $\Omega$, is presented in Fig. 3. The $S_{11}$ parameter
is below the -10 dB from 12 GHz to 20 GHz. The small period
oscillations are associated to double reflections at the lens-air
interface [7].

![Graphs of radiation patterns](image)

Fig. 4. Radiation pattern for the wide band design: (a) $E$-Plane; (b) $H$-Plane.

The radiation patterns of the wide band antenna have been
measured in the range from 13 GHz to 17 GHz. The antenna
pattern has a pointing angle essentially constant and its -3dB
angle shows a limited variation over a large bandwidth. This
antenna is probably the first one to present such property
among leaky wave antennas. The measured directivities are
reported in Table I. The directivity calculated at 13 GHz, using
HFSS is also reported and it is in very good agreement with
the measured one. One can note that the directivity increases
very moderately over the investigated frequency range.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Measured Directivity (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>17.389 (17.6 HFSS)</td>
</tr>
<tr>
<td>14</td>
<td>18.446</td>
</tr>
<tr>
<td>15</td>
<td>18.216</td>
</tr>
<tr>
<td>16</td>
<td>18.834</td>
</tr>
<tr>
<td>17</td>
<td>19.109</td>
</tr>
</tbody>
</table>

TABLE I
MEASUREMENT DIRECTIVITY.

The normalized measured radiation patterns at 3 frequencies
(13, 15 and 17 GHz) of the wide band antenna are presented
in Fig. 4(a) ($E$-plane) and Fig. 4(b) ($H$-plane). The $E$-plane
pattern is fairly symmetric and if one concentrates on the
-3 dB radiation it varies from 18 degrees to 16 degrees in
the considered frequency range, maintaining the same
pointing angle. The same cannot be said for $H$-plane due to
the frequency dependent focusing effect of the lens. In this
case the -3dB beamwidth shows a variation from 18 to 25
degrees. In the same figure, for both $E$- and $H$-plane, we also
report the radiation patterns calculated by means of HFSS
(at 13 GHz only). These show a good agreement with the
measurement. No real optimization of the radiation pattern has
been performed due to limitations in the available modelling
tools. The design has been based on intuition and frequency
independent considerations only, therefore these results should
be regarded as extremely encouraging.

B. Dual Band Antenna

For the dual band antenna it has been decided to choose a
frequency ratio approximately 1 to 2. The restriction to
two operation frequencies is just for the sake of simplicity
in the design of the filtering structure needed to isolate the
two feeding points. Indeed there is no intrinsic limitation in
the proposed design preventing the use over an arbitrary set of
central frequencies. The dual band prototype has been manu-
factured and tested after the wide band version and therefore
it benefits of the experience gained with the first one. The two
central frequencies are 10.5 GHz and 22.5 GHz respectively.
The measured $S$ parameters in a band from 5 to 30 GHz are
reported in figures 5 (a) ($S_{11}$ parameters), (b) ($S_{12}$ parameters)
and (c) ($S_{22}$ parameters). In all three figures the measured
data (solid lines) is compared directly with the calculated data
dashed lines) from Ansoft Designer. Each one of the channels
has a very broad band which is restricted only by the isolating
stubs adopted in the filtering feed structure. Assuming -13 dB
as maximum acceptable levels for the reflection ($S_{11}$) and the
isolation ($S_{12}$) parameters, the following bandwidths can be
observed: from 9 GHz to 14 GHz for the lower frequency
(43%) and from 20 to 25 GHz (19%) for the higher frequency.
The agreement between measured and calculated $S$ parameters
is outstanding. This is remarkable, especially considering that
for this dual band antenna the time gating to extract the coax
to CPW transition was not used. The oscillation of relatively large
period reported in the calculations and in the measurements are due to mismatches between the coax to CPW transition caused by the dispersive behavior of the CPW. This oscillations could be avoided by decreasing the minimal slot’s width to 0.05 mm or using an integrated receiver characterized by higher impedance or using microstrip type of feeding. The oscillations of smaller period, observed in the measurement only, are the effect of the reflections at the dielectric interface.

The measured radiated fields at 10.5 GHz and 22.5 GHz are reported in figure 6. The radiated fields in both E and H planes are shown. In the H-plane the maximum radiated field at 22.5 GHz is shifted of 3.5 degrees with respect to the one at 10.5 GHz. This shift is small compared to beamwidth and essentially due to a slight asymmetry of the beam rather than to a depointing.

IV. CONCLUSION

A novel broad-band and directive leaky wave antenna has been presented. The unique feature of this antenna is that its main beam of radiation remains substantially the same at different frequencies. To our knowledge a leaky wave antenna whose pointing angle is essentially constant and with limited variation of the -3dB angle over a significant frequency sweep (one octave) has never been reported before. This is due to the peculiar radiation mechanism that has found here its first application. Two prototypes have been designed, manufactured and measured. The agreement between measurements and calculations proves the repeatability of the design, which is in large part based on basic, frequency independent, physical concepts.

The performances of this leaky wave lens antenna are comparable to those of long tapered slot (LTS) antennas [8]. With respect to LTS antennas they present significantly broader bandwidths, however they require a dielectric lens which makes them bulky at low frequencies. The directivity is such that the system can be used both as a self standing integrated receiver or as feed of a reflector system.

REFERENCES