WAVEGUIDE-FED BACKFIRE ANTENNAS FOR LOW-TERAHERTZ FREQUENCIES

H. D. Hristov[1], M. S. Leong[2], M. B. Perotoni[3], G. S. Kirov[4], and W. Grote[1]

[1]*Department of Electronics, UTFSM, Valparaíso, Chile, hristo.hristov@usm.cl*

[2]*Department of Electrical and Computer Engineering, NUS, Singapore 119077, msleong@nus.edu.sg*

[3]*Department of Information Engineering, UFABC, Brazil CEP 09210-170, Marcelo.Perotoni@cst.com*

[4]*Department of Radiotechnics, Technical University, Varna, Bulgaria, 9010, gkirov@abv.bg*

Abstract

Two X-band backfire antenna designs, proposed and studied years ago by the first and second co-authors, have been re-designed and examined numerically for the low-terahertz (THz) frequency range of 200-300 GHz. For the same gain and transverse aperture, the wavegude-fed backfire antennas, the long (LBFA) and short (SBFA) are very compact in length compared to the optimally designed classical horn. It was found that the presence of dielectric rod element in the LBFA can diminish considerably antenna gain and radiation efficiency. The SBFA is extremely compact and possesses a superior gain and input match bandwidth. Up to 500-600 GHz the miniature backfire antennas can be easily produced by means of precise micromachining technologies.

1. INTRODUCTION

Long backfire antenna (LBFA) originated from the endfire antenna (EFA) by setting the EFA between two plane reflectors: small or endfire and large or backfire [1], [2]. The classical microwave LBFA is fed by a dipole plus small reflector assembly, which launches the surface wave (SW) along the EFA structure. The large reflector acts as a plane mirror that turns the surface wave backward, and thus forcing it to traverse the antenna length multiple times. As a result, the LBFA is acting as an open-end radiating resonator, similar to the Fabry-Perot laser cavity. Thus, the dominant LBFA mode is a standing wave along the SW structure. For centimetre and millimetre waves the backfire antenna with a waveguide-fed SW structure is more natural choice [3]-[5].

If the distance between the large and small reflectors is only about a half wavelength the SW structure becomes redundant. Such antenna is called short backfire (SBFA). Depending on its resonant frequency the SBFA is fed by either a dipole between the reflectors, or by an open-ended waveguide at the side of the large reflector [5], [6]-[8]. With a radiation aperture of about two wavelengths as a rule and an axial length of about a half wavelength the dipole-fed LBFA is very compact and highly efficient radiator with a gain of about 14-17 dB.

Two X-band backfire antenna constructions proposed and studied experimentally years ago by the first [4] and second [8] co-authors are re-designed and examined numerically for the low-terahertz (THz) frequency range of 200-300 GHz by means of the CST Microwave Office electromagnetic solver [9].

The terahertz waves occupy a relatively unfamiliar portion of the electromagnetic spectrum between the infrared and microwave bands (100-10000 GHz). The frequency band from 100 GHz to 3000 GHz is normally called a low-terahertz or millimetre-wave band. The terahertz waves are of particular interest for imaging of biological objects because of their non-ionizing nature, which renders them as non hazardous for human, unlike X-rays, for instance. Until now, they have been used mainly for space, military and astronomy applications. New application areas found in medicine, the environmental and biological sciences, as well as in security and quality control-have emerged only recently. These drive terahertz research towards cheaper, room-temperature components, including focusing/imaging lenses and antennas, and hence pave the way for terahertz short-range wireless communication systems.

2. LONG BACKFIRE ANTENNA WITH WAVEGUIDE-FED DIELECTRIC ROD

2.1. Antenna geometry and dimensions

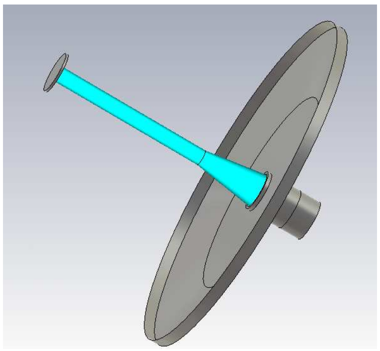
The antenna are fed by a circular TE_{11}-mode waveguide with an inner diameter of 0.97 mm, inserted through the big reflector and terminated by an input flange.

Fig. 1 shows the simulation model of a five wavelengths long LBFA designed at a frequency of 240 GHz (or at a wavelength of $\lambda_0 = 1.25$ mm). It is fed by a round waveguide 1.06 mm in diameter. Through a conical portion of 1.875 mm the rod diameter is decreased to 0.339 mm for producing a loose surface wave along the rod. The large rimmed reflector is plane-conical in shape with an outer diameter of 9.43 mm (7.54 λ_0). The small reflector is a disk 1.1 mm in diameter. LBFA antenna length (or the distance between reflectors) is equal to 6.26 mm (5.0 λ_0). The plane area of large reflector has a diameter of 5.63 mm (7.54 λ_0), and its cut-cone section is 0.31 mm (roughly 0.25 λ_0) in length. The same size (width) has the reflector rim.

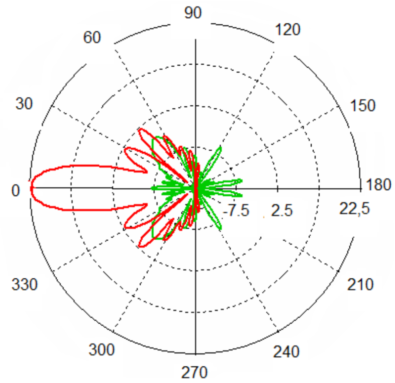
2.2. Numerical results for LBFA

In this section are shown the essential radiation and input antenna characteristics found by means of numerical simulation [9] of the LBFA design, shown in Fig. 1(a). Fig. 1(b) illustrates the co- and cross-polarization gain patterns for the LBFA antenna simulated as an ideal construction made of lossless metal with a conductivity $\sigma = \infty$ and dielectric with a relative permittivity $\varepsilon = 2.1$. The co-polar gain pattern (line with a dot at the pattern maximum) shows a peak directive gain of about 22.5 dBi, while the first and second sidelobes are 20 dB down. Since the large rimmed reflector overshadows the rear hemisphere the back co-polar pattern level is very small- less than 40 dB down to the peak gain.

Theoretically the HE_{11} hybrid SW wave in the dielectric rod fed by the TE_{11}-mode metal waveguide is notable by its quasi-plane transverse-field structure In addition, the LBFA reflectors do not change the radiation field polarization considerably. For the rather tiny antenna size the LBFA has a low cross-polar pattern with a level of about 30 dB down to the peak co-polar gain.



(a)



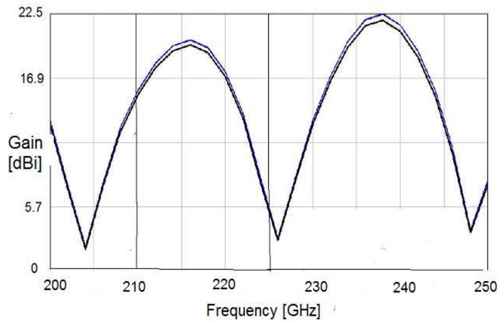
(b)

Fig. 1. Waveguide-fed LBFA with plane-conical large reflector: (a) LBFA design model, and (b) 45-degree cut plane co-polar (line with big main lobe of 22.5 dBi) and cross-polar pattern (low-level pattern) of LBFA made of idealized (lossless) metal and dielectric

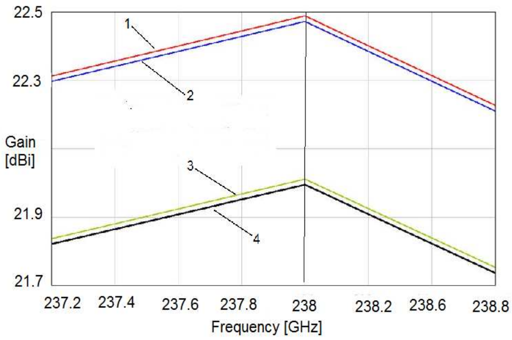
Fig. 2 shows the frequency peak gain variation of the idealized (upper line) and real (lower line) LBFA models within 200-250 GHz frequency range. The upper and lower lines correspond to the directive gain and input gain respectively The input gain includes losses of the construction materials (metal and dielectric) and is smaller than the aperture directive gain. For the studied LBFA it is assumed that all metal components (waveguide, large and small reflectors) are golden (conductivity $\sigma = 4.1.10^7 \mathrm{S/m}$) and the SW dielectric rod is made of Teflon (complex permittivity $\varepsilon = 2.1 - j0.05$).

Fig. 2(a) shows that in the frequency band 200-250 GHz the studied LBFA exhibits two gain maximums: at around 216 GHz and 238 GHz. The second gain maximum of the lossless antenna is 22.4 dBi high, which corresponds to an aperture radiation efficiency of 60 %. The first maximum is by 2.6 dB lower than the second one and could be ignored. Thus, only the antenna behavior around 238 GHz will be discussed. It is found that the -3 dB gain bandwidth around the optimum frequency of 238 GHz is about 8.3 GHz (or 3.5%) for both LBFA models: ideal and real. In conclusion, judging by the gain bandwidth the LBFA is a narrowband antenna.

Fig. 2(b) illustrates zoomed in the gain graph pieces close to the optimum frequency of 238 GHz for four material scenarios, specified in the figure´s legend. Lines 1 and 4 correspond to the upper and lower graphs in Fig. 2(a), respectively. The two VSWR curves in Fig. 3 illustrate the input match properties of the examined antenna for a lossless (ideal) model (upper graph) and for a real model made-up by metal (gold) and dielectric (Teflon), (lower graph). For VSWR less than 2.0 the LBFA exhibits a frequency bandwidth input frequency range of 10.7 GHz, or 4.5 % relative to the optimum gain frequency of 238 GHz. At the same frequency the real antenna model has VSWR=1.7, which corresponds to a small mismatch loss of 0.3 dB. From Fig. 2 and Fig. 3(a) can be concluded that (i) at the optimum frequency of 238 GHz the total gain loss is about 0.65 dB, from which only less than 0.05 is produced by the metal loss. In other words, at the low-terahertz frequencies both dielectric and mismatch loss are of importance for the realized input antenna gain.



(a)



(b)

Fig. 2. LBFA gain vs frequency: (a) normal scale graphs for lossless antenna model (upper graph) and for antenna construction made of genuine metal (gold) and dielectric (Teflon), (lower graph); (b) zoomed in pieces of graphs for four material scenarios: 1-lossless metal and dielectric (idealized case), 2-genuine gold and lossless dielectric, 3-lossless metal and genuine dielectric (Teflon) and 4- genuine gold and Teflon (authentic case)

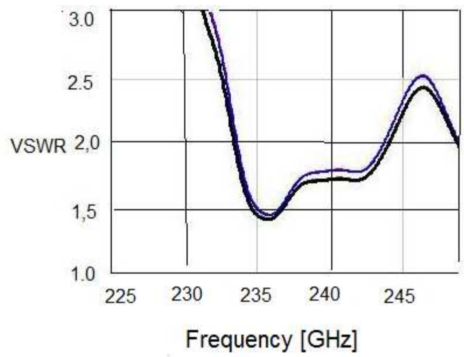


Fig. 3. LBFA input VSWR vs frequency for lossless antenna model (upper graph) and for antenna made of real metal (gold) and dielectric (Teflon), (lower graph

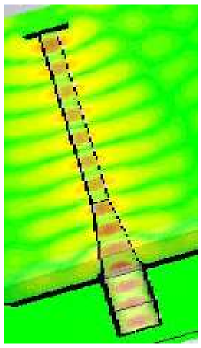


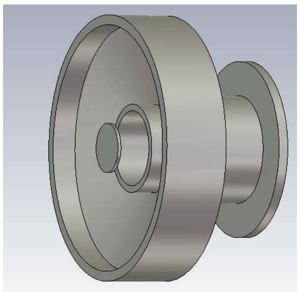
Fig. 4. LBFA: picture of inner standing-wave field distribution

By both gain and input match criteria the LBFA is classified as a narrowband antenna with a relative bandwidth of about 3-4 %. This is due to the antenna standing-wave field density structure inside and outside the dielectric rod as illustrated in Fig. 4. Ten half-wave field maxima (and minima) along the antenna axis are counted between the big and small reflectors, which corresponds to the five-wavelength antenna length. Regardless of its narrowband categorization the low-terahertz frequency LBFA can work in a big frequency range of about 10 GHz and possesses a great signal communication capacity.

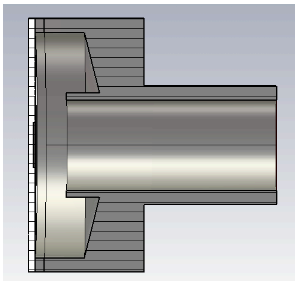
3. WAVEGUIDE-FED SBFA

3.1 Antenna design

Fig. 5(a) is a 3D artistic view of waveguide-fed SBFA with a slightly-conical large reflector. The actual SBFA construction, described in this paper, is illustrated in Fig. 5(b) by its axial cross section, where the antenna aperture is covered by a thin Teflon disk (radome), 0.15 mm in thickness, the large reflector rim is extended to the radiation aperture and the waveguide input flange is ignored in this drawing.



(a)



(b)

Fig. 5. Waveguide-fed SBFA design with conical large reflector, (a) 3D antenna picture, and (b) axial plane-cut section with dielectric-covered aperture

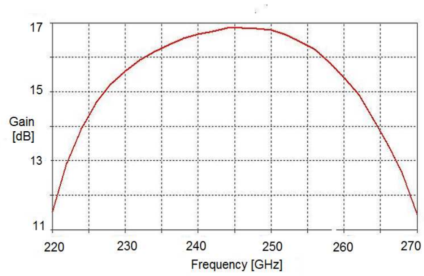
The studied SBFA is two-and-half wavelengths, or 3.2 mm, in diameter. The small reflector is a disk with diameter of 0.64 mm, and SBFA is just a half-wavelength (0.62 mm) long. The antenna is fed by a circular TE_{11}-mode waveguide with an inner diameter of 1.26 mm. The feed waveguide is inserted through the big reflector, and terminated by a round input flange. This SBFA somewhat differs from the original configuration described in [8], where a rectangular waveguide is utilized.

3.2. Numerical results

The SBFA consist basically from metal (golden) elements. The dielectric cover disk is too thin and practically lossless. Our computer simulation has proved that the dielectric and metal losses jointly make very small reduction of antenna gain (less than 0.1 dB in the 220-270 GHz range of interest). From this follows that the input antenna gain will be roughly equal to its directive gain (directivity) in case of very good input match, or if VSWR is near to less than 1.5.

From Fig. 6(a) is calculated that the studied SBFA has a maximum directive gain of about 17 dBi at a slightly higher optimum frequency of 245 GHz. The SBFA gain bandwidth, calculated at levels -3 dB down to the maximum directive gain is about 16 %.

Besides, the input match bandwidth, calculated from the VSWR vs frequency curve in Fig. 6(b) at the level VSWR=2 is 14.7 %. or it is very similar to the directive gain bandwidth.



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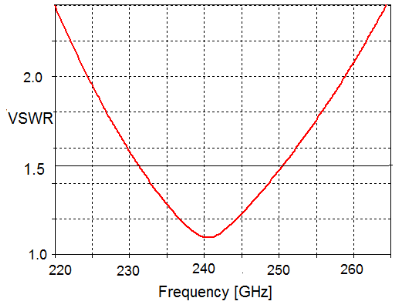
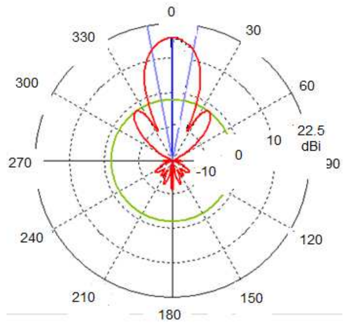


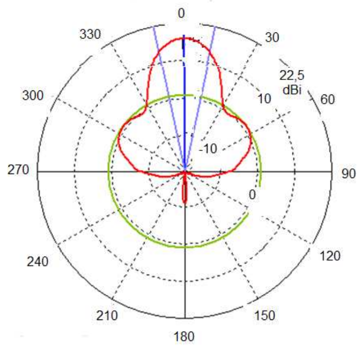
(b)

Fig. 6. SBFA directive gain (a) and input VSWR (b) versus frequency

Fig. 7 illustrates both E-plane (a) and H-plane (b) SBFA directive gain radiation patterns.



(a)



(b)

Fig. 7. Co-polar directive gain patterns of SBFA: (a) E-plane cut and (b) H-plane cut

For a very good match (say for VSWR < 1.2) the realized input gain for the frequencies close to the SBFA resonant frequency is practically equal to the antenna directive gain. The studied SBFA configuration has a high radiation aperture efficiency of about 80 %.

In addition, the antenna is extremely compact. Compared to a standard conical horn with the same gain and radiation aperture diameter, the studied SBFA is about 7-8 times shorter.

4. COMPARISON BETWEEN LBFA AND SBFA

Next LBFA and SBFA are contrasted by their dimensions (Table 1) and basic electromagnetic characteristics (Table 2).

In Table 1 are listed D_{BFA} (the aperture diameter) and L_{BFA} (the antenna length) relative to the corresponding BFA wavelength λ_0. In addition, the ratios between L_{Con} and L_{BFA} are given, where L_{Con} is the length of the conical antenna having an aperture diameter and directive gain equal to those of the corresponding backfire antenna (LBFA or SBFA).

Table 1. Contrast of dimensions

	$\frac{D_{BFA}}{\lambda_0}$	$\frac{L_{BFA}}{\lambda_0}$	$\frac{V_{BFA}}{\lambda_0^3}$	$\frac{L_{Con}}{L_{BFA}}$
LBFA	7.5	5.0	220	2.6
SBFA	2.5	0.6	2.9	7.3

Table 2. Comparison of main antenna parameters

	Gain [dBi]	SL [dB]	BL [dB]	Xpol [dB]
LBFA	22.5	-20	-40	-30
SBFA	16.9	-17	-27	-17

Table 2. (Continuation)

	Band width [%]	Eff_a [%]	Eff_t [%]
LBFA	3.5	60	52
SBFA	14.5	80	79

In Table 2 are compared the following LBFA and SBFA parameters: SL (side lobe level), BL (back lobe), Xpol (max 45-deg cross polar level), Eff_a (aperture efficiency) and Eff_t (total efficiency, which includes material losses).

5. CONCLUSIONS

Two backfire antennas, the LBFA and SBFA, have been studied as possible candidates for the low-terahertz band. It was found that the dielectric rod element in the LBFA is the major source of loss and can diminish considerably the antenna gain and radiation efficiency. The SBFA is extremely compact and possesses a superior gain and input match bandwidth. Up to 500-600 GHz the miniature backfire antennas can be easily produced by means of precise micromachining technologies.

6. ACKNOWLEDGMENTS

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