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# Multifunctional Angular Bandpass Filter SIW Leaky-Wave Antenna

Alejandro Javier Martínez-Ros, *Student Member, IEEE*, José Luis Gómez-Tornero, *Member, IEEE*, and George Goussetis, *Senior Member, IEEE*

**Abstract**—The synthesis of broad-beam radiation patterns with increased angular rejection and bandpass filtering functionalities from a rectilinear leaky-wave antenna is proposed. A sharpened angular filter response is obtained with shorter antennas, by introducing radiation nulls adjacent to a synthesized broad-beam. Moreover, exploiting the inherent dispersive properties of LWAs, aforementioned features can be combined with bandpass frequency filtering characteristics. These angular and bandpass filtering functionalities are validated with experiments performed on fabricated prototypes in modulated substrate integrated waveguide (SIW) technology. An enhancement in the angular rejection from  $1 \text{ dB}^\circ$  to  $2.5 \text{ dB}^\circ$  is demonstrated for a  $20\lambda_0$ -long antenna with a broad main beam covering the range  $[20^\circ, 40^\circ]$  at 15 GHz, and with a simultaneous bandpass in the  $[14 \text{ GHz}, 19 \text{ GHz}]$  band.

**Index Terms**—Angular filters, antenna synthesis, broad-beam antennas, leaky-wave antennas, substrate integrated waveguide.

## I. INTRODUCTION

BROAD-BEAM leaky-wave antennas (BB-LWAs) were first proposed for the synthesis of radiation patterns with an optimized main beam covering a specified wide angular region [1]. This type of selective broadbeam patterns are of particular interest for indoor WLAN applications [1], or cosecant beam shaping [2]. For that purpose, Ohtera proposed the bending of the leaky-wave line along its longitudinal direction, so that the BB pattern can be directly related to the curved geometry and the fixed leaky-wave propagation constant [1]. Later, Burghignoli et al. [3] proposed a technique to obtain broadbeam shaping by modulating the leaky-wave complex propagation constant along a rectilinear aperture, thus avoiding curved structures. This synthesis technique was modified in [4] to include radiation nulls in prescribed angular regions, which was demonstrated for substrate integrated waveguide technology (SIW) technology in [5]. By using the selective properties of the synthesized radiation patterns proposed in [4], an application as a highly integrated SIW angular filter can be devised. **Compared to previous related filtering designs based on frequency selective surfaces (FSS) [6]–[10],**

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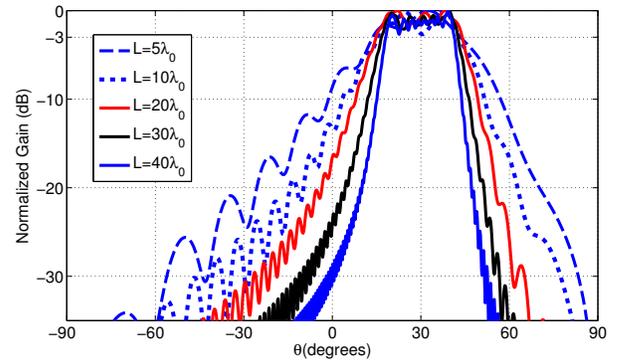


Fig. 1. Theoretical BB radiation patterns as a function of LWL length  $L$ .

**this approach incorporates angular/frequency filtering in the radiating element.** As seen in Fig. 1, the angular rejection on BB-LWAs depends on the radiating length  $L$ . One contribution of this letter is to demonstrate that by properly modulating the leaky mode similar rejection can be obtained using only half radiating length  $L$ . Also, the inherent dispersion properties of LWAs can be used to combine the angular filtering mechanism with the bandpass frequency response. In this manner, combined angular-frequency filtering can be conceived in the frame of highly-integrated multifunctional antennas, i.e., antenna designs integrating functions additional to EM radiations in a single device [11]. A further contribution of this letter is to present for the first time a SIW LWA which simultaneously performs this interesting angular/bandpass filtering response with flexible design specifications in both angular and frequency domains. The proposed SIW LWA technology integrates into a single planar device the radiating and filtering mechanisms, being therefore a much more compact solution in contrast to previous (FSS) [6]–[10]. The rest of the work is organized as follows. Section II describes the theoretical concepts, which are based on the synthesis of radiation nulls [4] at both angular regions surrounding the prescribed wide beam. In Section III, this is applied to the study of the frequency response and the capability of this leaky-wave device for behaving as a selective angular bandpass filter in SIW technology. Finally, the main conclusions of this work are summarized in Section IV.

## II. SYNTHESIS OF ANGULAR FILTERING RESPONSE

The design of rectilinear BB-LWA is based on the suitable modulation of the leaky-wave complex propagation constant along the LWA length [3], [12]. Fig. 1 illustrates the radiation

patterns obtained when applying this BB leaky modulation technique with different LWA lengths  $L$ , for the synthesis of a broadbeam centered at an angle  $\theta = 30^\circ$  with a  $-3$  dB beamwidth of  $\Delta\theta = 25^\circ$ . Clearly, one needs higher values of  $L$  to synthesize a more selective angular response while keeping the same main beam width. This is summarized in Table I, which illustrates the rejection out from the prescribed wide beam (measured as the linear slope in dB/° to fall from  $-3$  dB to  $-10$  dB), as a function of  $L$ .

TABLE I  
RELATION BETWEEN ANGULAR REJECTION AND BB LWA LENGTH.

Length $L$	$5\lambda_0$	$10\lambda_0$	$20\lambda_0$	$30\lambda_0$	$40\lambda_0$
Rejection dB/°	0.5	0.7	1	1.5	2.4

The standard modulation technique proposed in [3], can be modified with the addition of more demanding specifications, so that the angular rejection can be increased without the need of enlarging the LWA. To this aim, the numerical technique for the efficient synthesis of radiation nulls in rectilinear tapered LWAs proposed in [4] has been used. This is illustrated in Fig. 2, where it is plotted in magenta the theoretical radiation pattern obtained for a  $20\lambda_0$ -long tapered LWA with the following specifications: a main broad-beam with a  $-3$  dB width covering the angular range  $\theta = [20^\circ, 40^\circ]$ , and two radiation nulls below  $-20$  dB in the angular regions  $\theta = [0^\circ, 15^\circ]$  and  $\theta = [45^\circ, 60^\circ]$  surrounding the two sides of this main wide beam (these specs are plotted with green dashed lines in Fig. 2). It can be seen that the designed  $20\lambda_0$ -long tapered LWA has the same rejection than a  $40\lambda_0$ -long LWA using the standard BB tapering technique (plotted in blue line), thanks to the addition of the null specs. Out from these null regions, the designed  $20\lambda_0$  LWA follows the radiation profile of a conventional tapered BB  $20\lambda_0$ -long LWA (plotted in dashed red line), as it can be also seen in Fig. 2 for  $\theta < 0^\circ$ . This is due to the fact that our design is based on a conventional  $20\lambda_0$  BB in which null specs have been added only to the prescribed angular regions.

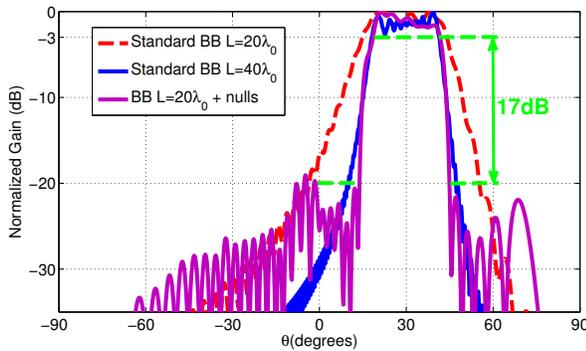


Fig. 2. Synthesis of radiation nulls to increase the angular rejection.

In Fig. 3 there are shown the requested simultaneous tapering functions for the leaky-wave pointing angle  $\theta_{RAD}(z)$  and normalized leakage rate  $\alpha(z)/k_0$  to synthesize the two  $20\lambda_0$  BB-LWA designs of Fig. 2. It is shown how the conventional

BB tapering [3] (solid line) involves a quasi-linear increase in the tapered pointing angle covering the angular region  $\theta_{RAD}(z) = [10^\circ, 50^\circ]$  (see Fig. 3a), while modulating the leakage rate in order to provide uniform radiated power per unit angle in the aforementioned interval (see Fig. 3b). However, these smooth tapering functions for the BB-LWA are modified with abrupt variations (dashed line) in both  $\theta_{RAD}(z)$  and  $\alpha(z)/k_0$  to synthesize the requested radiation nulls, being these variations stronger for wider and deeper null specs as explained in [4].

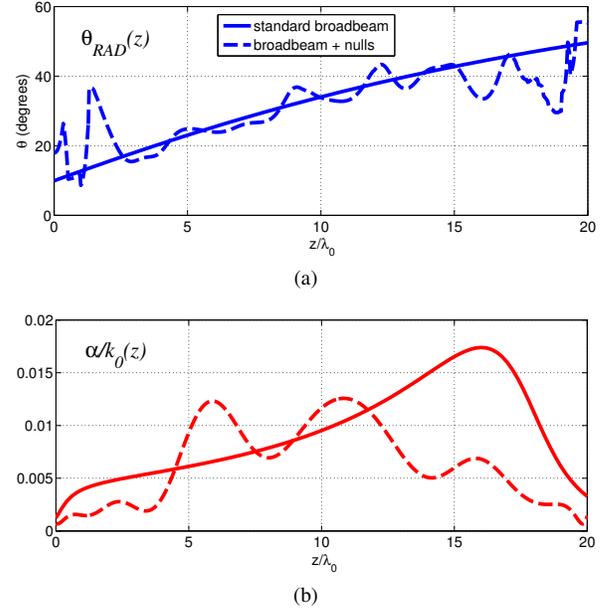


Fig. 3. Tapering of leaky-wave a) pointing angle and b) leakage rate for BB synthesis and generation of radiation nulls.

The electrical modulations in the leaky-wave complex propagation constant must be translated into geometrical modulations of the antenna cross section along its length  $z$ . Here we propose the use of a SIW LWA, which has recently shown the capability to flexibly control  $\theta_{RAD}$  and  $\alpha/k_0$  by properly designing the SIW width  $W$  and the separation between vias  $P$  [13], as sketched in Fig. 4a. In this way, the requested LW modulation of Fig. 3 is transformed into the SIW geometry modulation functions  $W(z)$  and  $P(z)$  shown in Fig. 4b, for both  $20\lambda_0$  tapered designs (standard BB and BB with nulls). In order to manufacture the prototypes a design frequency of 15 GHz ( $\lambda_0 = 20$  mm), and a commercial substrate with  $\epsilon_r = 2.2$ ,  $\tan\delta = 0.0009$  and  $h = 0.508$  mm have been chosen. A photograph of the fabricated modulated SIW prototype is shown in Fig. 5a, and the measured radiation pattern at 15 GHz for the BB-with-nulls design (dashed red line) is compared with theory (solid blue line) in Fig. 5b. The dimensions of the SIW LWA prototype are  $450 \times 40 \times 0.508$  mm, and SMA connectors are used to inject power in the antenna and to connect the output with a matched load at Port 2. As it can be seen, good agreement between experiments and desired pattern is obtained, showing the synthesis of a very selective broad-beam covering the prescribed  $-3$  dB angular region  $\theta = [20^\circ, 40^\circ]$ , and with the desired sharp angular response. Some discrepancies are

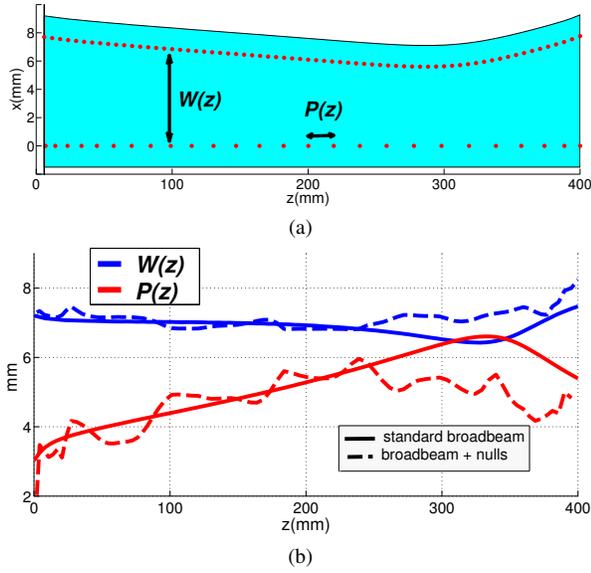


Fig. 4. a) Scheme of modulated SIW LWA with  $L = 20\lambda_0 = 400$  mm. b) Tapering of SIW dimensions for BB synthesis and generation of radiation nulls.

observed in the angular range  $\theta = [-20^\circ, -40^\circ]$ , due to the leaky wave reflected at the far end of the LWA (which emits energy at mirrored angles with respect to the main beam). Moreover, to stress the improvement in the angular rejection due to the unconventional tapering of the leaky wave, the measured radiation pattern for the conventional BB tapered SIW design (green line) is shown in Fig. 5b. Quantitatively, the measured rejection has increased from 1 dB/° to 2.5 dB/° as a result of the new tapering technique, thus demonstrating the synthesis of a BB from modulated rectilinear LWAs, and the increase in the angular rejection by using leaky-wave null-synthesis techniques.

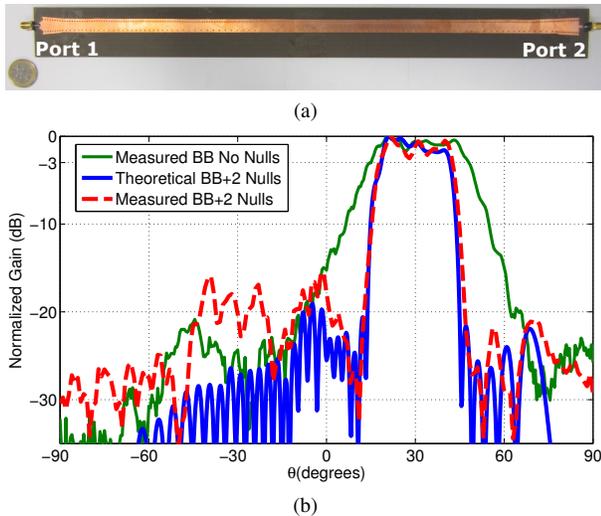


Fig. 5. a) Modulated BB SIW prototype and b) measured radiation pattern showing angular filtering response at 15 GHz.

### III. SYNTHESIS OF BANDPASS FREQUENCY RESPONSE

The frequency response of angular filters is also of key importance to permit the desired bandwidth and to reject

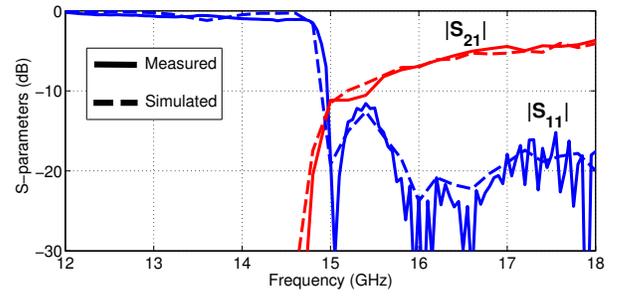


Fig. 6. Measured and simulated  $S$ -parameters for the BB-with-nulls SIW LWA.

unwanted channels, thus behaving as angular bandpass filters [8]. As it is well-known, the main beam of a LWA is frequency scanned as a result of the dispersive nature of leaky mode, and this also happens in BB designs as theoretically demonstrated in [12]. Due to the antenna needs to operate in a large bandwidth, e.g., from 15 GHz to 18 GHz, it is important that the antenna is well matched along the entire band. As it can be seen in Fig. 6, the measured input matching  $S_{11}$  is kept below  $-10$  dB for the entire band from 15 GHz to 18 GHz, which allows its use for this range of frequencies. Also, it is worth to note that at the design frequency of 15 GHz the measured  $S$ -parameters show a  $S_{11} \approx -20$  dB and a low  $S_{21} \approx -10$  dB as a result of the high designed radiation efficiency [13].

With the aim of showing the frequency response for the BB-with-nulls SIW LWA, the measured gain patterns are plotted in Fig. 7 for the frequency range from 15 GHz to 18 GHz. As it can be seen, the main broadband covers different angular regions as frequency is shifted, showing a mean scanning ratio of  $SR = 15^\circ/\text{GHz}$ . This frequency scanning behavior can be used to determine the bandpass frequency response for a fixed observation angle  $\theta_0$ . In this manner, different observation angles or scanning ratios can be chosen in order to modify the bandpass frequency response. This frequency response is illustrated in Fig. 8 for an observation angle of  $\theta_0 = 30^\circ$  and a range of frequencies from 14 GHz to 17 GHz. In particular, it can be seen how the bandpass response  $G(f, \theta_0)$  is totally coupled to the angular response  $G(\theta, f_0)$  in Fig. 7, which is determined by the SIW leaky-mode frequency dispersion  $\theta(f)$ . For instance, in Fig. 8 it is shown the frequency response at a fixed observation angle  $\theta_0 = 30^\circ$ , which is in coherence with

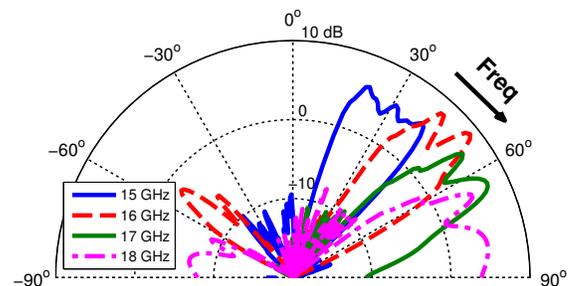


Fig. 7. Measured gain radiation patterns at several frequencies for a BB-LWA with nulls.

the angular pattern obtained at 15 GHz in Fig. 7. As frequency is varied, the BB with  $\Delta\theta = 20^\circ$  is scanned at the aforementioned ratio of  $15^\circ/\text{GHz}$  resulting in a mean  $-3\text{ dB}$  bandwidth of  $BW \approx 700\text{ MHz}$ , as shown in Fig. 8. However, due to the nonlinear leaky-mode dispersion, a ripple in the main beam and a not constant beamwidth are observed as frequency is varied (see Fig. 7). When compared to FSS-based angular bandpass filters which allow for an independent synthesis of frequency and angular responses [8], the proposed leaky-wave SIW device lacks of design flexibility. Nevertheless, this is due to its much simpler and integrated nature, which provides angular and frequency filtering from a single planar radiator.

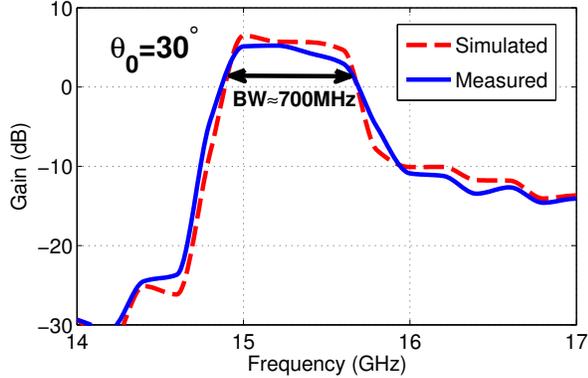


Fig. 8. Measured bandpass filtering response at a fixed observation angle  $\theta_0 = 30^\circ$  for a BB-LWA with nulls.

Finally, the simultaneous angular bandpass filtering functionality is illustrated in Fig. 9, which represents the measured gain vs frequency ( $y$ -axis) and angle ( $x$ -axis). This type of plot visually relates the dependence of the aforementioned beamwidth  $\Delta\theta$ , scanning ratio  $SR$ , and resulting bandwidth  $BW$ . It is observed how the  $20^\circ$ -broad main beam moves towards endfire as the frequency is increased, while keeping a sharp rejection in both angular and frequency domains. This high rejection is distorted by the reflected lobe at  $-\theta_{\text{RAD}}$ , created by the antenna end discontinuity. However, the measured level of the reflected lobe is  $10\text{ dB}$  below the main beam for all frequencies (see also Fig. 7).

#### IV. CONCLUSION

In this work it has been demonstrated for the first time the ability of a modulated SIW leaky-line, to simultaneously provide angular and bandpass filtering functionalities in a single, one-layer, low-profile planar device. Measured results on fabricated  $20\lambda_0$ -long prototypes operating at  $15\text{ GHz}$  with  $20^\circ$  broadbeam, have shown an increase in the angular rejection from  $1\text{ dB}/^\circ$  to  $2.5\text{ dB}/^\circ$  thanks to the addition of radiation null specs. Finally, the performance as a planar integrated angular bandpass filter in the  $[14\text{ GHz}, 19\text{ GHz}]$  band has also been reported. This type of multifunctional integrated SIW antenna topology might find application for future broadband, high-throughput, analog signal processing systems.

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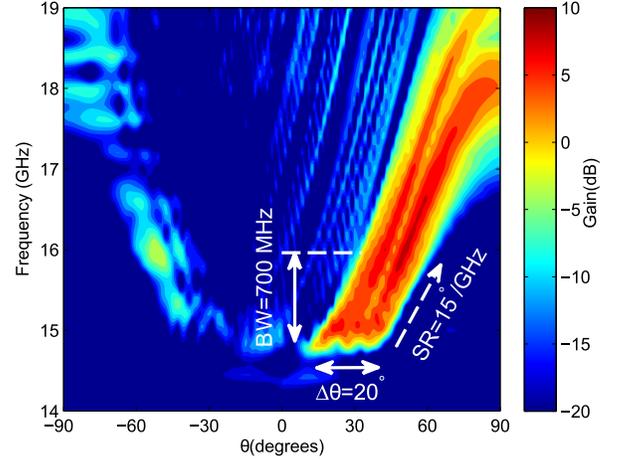


Fig. 9. Measured angular bandpass filtering performance for the BB-with-nulls LWA, where gain is represented by an intensity colorbar,  $\theta$  is in  $x$ -axis, and frequency in  $y$ -axis.

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