Multifunctional Angular Bandpass Filter SIW Leaky-Wave Antenna

Alejandro Javier Martinez-Ros, *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 (LWA) 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 a modulated substrate-integrated waveguide technology. An enhancement in the angular rejection from 1 to 2.5 dB/° is demonstrated for a $20\lambda_0$-long antenna with a broad main beam covering the range [20°, 40°] at 15 GHz and with a simultaneous bandpass in the [14 GHz, 19 GHz] band.**

***Index Terms*—Angular filters, antenna synthesis, broad-beam (BB) antennas, leaky-wave antennas (LWAs), substrate integrated waveguide (SIW).**

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]. These types of selective BB patterns are of particular interest for indoor wireless local area network 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 BB 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 the substrate-integrated waveguide (SIW) technology in [5]. By using the selective properties of the synthesized

Manuscript received May 4, 2016; revised July 5, 2016; accepted September 28, 2016. Date of publication October 3, 2016; date of current version April 17, 2017. This work was supported in part by the Juan de la Cierva Programme, in part by Ministerio de Educación y Ciencia and FEDER, Ref. TEC2013-47037-C5-5-R, in part by the ESF in the framework of the RNP-NEWFOCUS, and in part by FP7 project DORADA under Grant IAPP-2013-610691.

A. J. Martinez-Ros is with the Microwaves Group, Department of Applied Physics 1, Escuela Técnica Superior de Ingeniería Informática, Universidad de Sevilla, Seville 41012, Spain (e-mail: amartinez49@us.es).

J. L. Gómez-Tornero is with the Department of Communication and Information Technologies, Universidad Politécnica de Cartagena, Cartagena 30202, Spain (e-mail: josel.gomez@upct.es).

G. Goussetis is with the Institute of Sensors Signals and Systems, Heriot-Watt University, Edinburgh, EH14 4AS, U.K. (e-mail: g.goussetis@ieee.org).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LAWP.2016.2614914

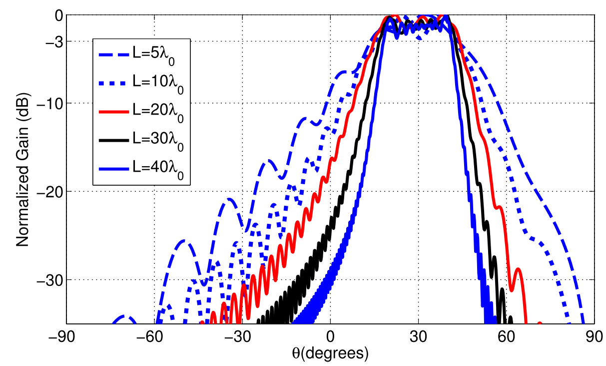


Fig. 1. Theoretical BB radiation patterns as a function of LWA length L.

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 (FSSs) [6]–[10], 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 electromagnetic radiations in a single device [11]. A further contribution of this letter is to present for the first time a SIW LWA that 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

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

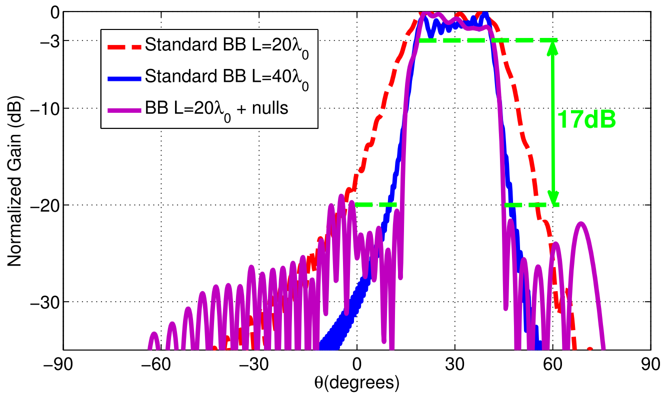


Fig. 2. Synthesis of radiation nulls to increase the angular rejection.

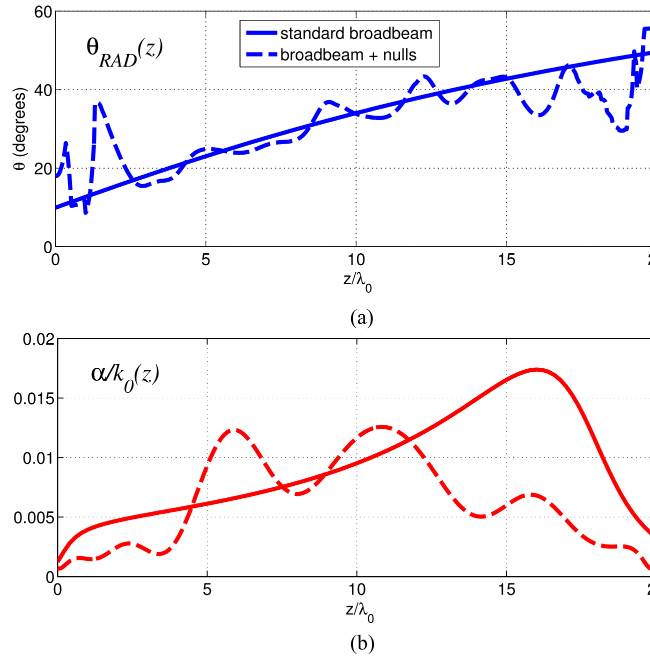


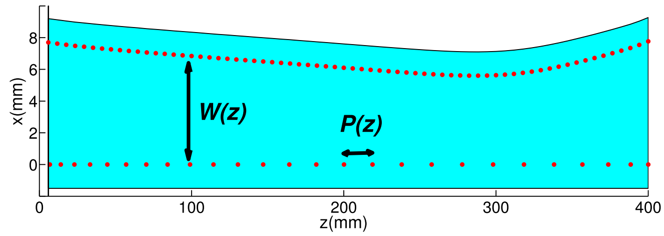
Fig. 3. Tapering of leaky-wave (a) pointing angle and (b) leakage rate for BB synthesis and generation of radiation nulls.

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 BB 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 beamwidth. 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 to -10 dB), as a function of L.

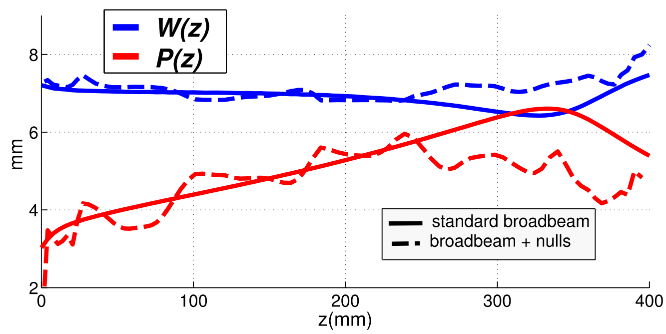
The standard modulation technique proposed in [3] can be modified with the addition of more demanding specifications, so that the angular rejection can be increased without the need of enlarging the LWA. To this aim, the numerical technique for the efficient synthesis of radiation nulls in rectilinear 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 is with the following specifications: a main BB with a -3-dB width covering the angular range $\theta = [20^\circ, 40^\circ]$, 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 as a $40\lambda_0$-long LWA by 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.

The requested simultaneous tapering functions for the leaky-wave pointing angle $\theta_{\mathrm{RAD}}(z)$ and normalized leakage rate $\alpha(z)/k_0$ to synthesize the two $20\lambda_0$ BB-LWA designs of Fig. 2 are shown in Fig. 3. 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 $\theta_{\mathrm{RAD}}(z) = [10^\circ, 50^\circ]$ [see Fig. 3(a)] while modulating the leakage rate in order to provide uniform radiated power per unit angle in the aforementioned interval [see Fig. 3(b)]. However, these smooth tapering functions for the BB-LWA are modified with abrupt variations (dashed line) in both $\theta_{\mathrm{RAD}}(z)$ and $\alpha(z)/k_0$ to synthesize the requested radiation nulls, being that these variations are stronger for wider and deeper null specs as explained in [4].

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 an SIW LWA, which has recently shown the capability to flexibly control θ_{RAD} and α/k_0 by properly designing the SIW width W and the separation between vias P [13], as sketched in Fig. 4(a). 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. 4(b), 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. 5(a), and the measured gain pattern at 15 GHz for the BB-with-nulls design (solid line) and without nulls (dashed line) is shown in Fig. 5(b). The dimensions of the SIW LWA prototype are $450 \times 40 \times 0.508$ mm^3, 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 BB covering the prescribed -3 dB angular region $\theta = [20^\circ, 40^\circ]$, and with the desired sharp angular response. Some discrepancies are observed in the angular range $\theta = [-40^\circ, -20^\circ]$, due to the leaky wave reflected at the far end of the LWA and the abrupt modulation of the SIW geometry. However, the angular rejection has increased from 1 to 2.5 dB/°, thus demonstrating the practical benefit of us-



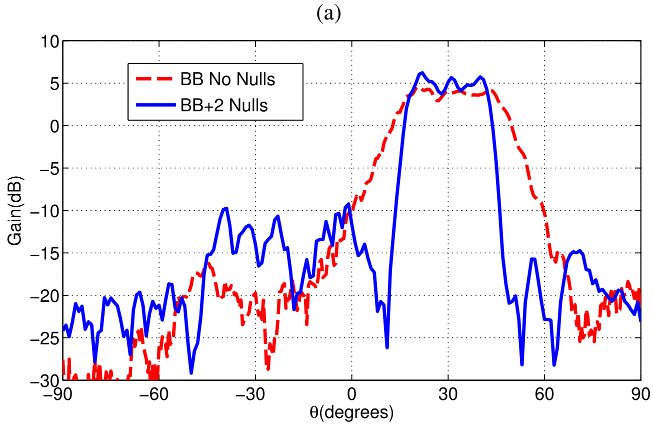
(a)



(b)

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.

(a)



(b)

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

ing leaky-wave null-synthesis techniques. As it can be observed in Fig. 5, the BB-with-nulls design provides 2 dB higher gain than the BB without nulls due to the more selective angular response. Also, the radiation efficiency measured from the gain to directivity ratio is of 50% for both designs. Moreover, it can be seen that a higher ripple level appears inside the main beam ($\theta = [20^\circ, 40^\circ]$) for the BB-with-nulls case in comparison to the BB-without-nulls one, which can be attributed to the more demanding tapering function that makes its synthesis difficult. As explained in detail in [12], the ripple level can be reduced by tapering the antenna aperture distribution at the expense of losing angular coverage or angular rejection.

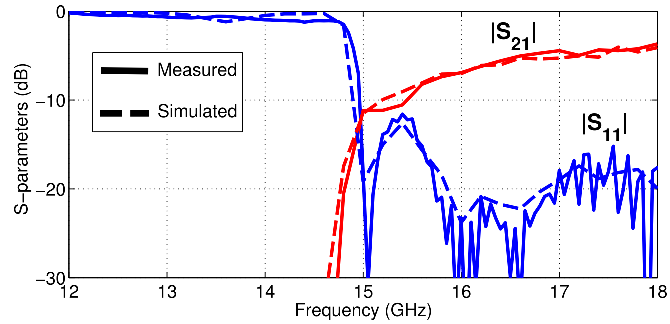


Fig. 6. Measured and simulated S-parameters for the BB-with-nulls SIW LWA.

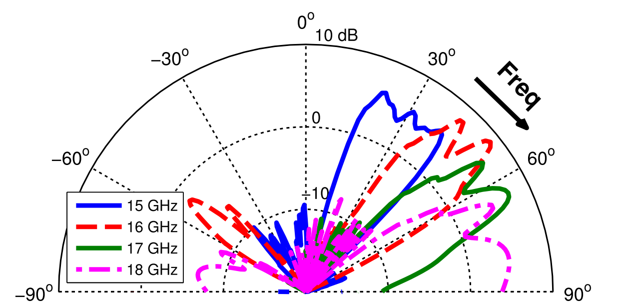


Fig. 7. Measured gain radiation patterns at several frequencies for a BB-LWA with nulls.

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 unwanted channels, thus behaving as angular bandpass filters [8]. As it is well known, the main beam of an 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]. Since the antenna needs to operate in a large bandwidth, e.g., from 15 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 to 18 GHz, which allows its use for this range of frequencies.

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 to 18 GHz. As it can be seen, the main BB covers different angular regions as frequency is shifted, showing a mean scanning ratio of SR $= 15^\circ$/GHz. This frequency scanning behavior can be used to determine the bandpass frequency response for a fixed observation angle θ_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 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, Fig. 8 shows the frequency response at a fixed observation angle $\theta_0 = 30^\circ$, which is in coherence with 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°/GHz, resulting in a mean -3-dB bandwidth of BW ≈ 700 MHz, as shown in Fig. 8. However, due to the nonlinear leaky-mode dispersion, the ripple

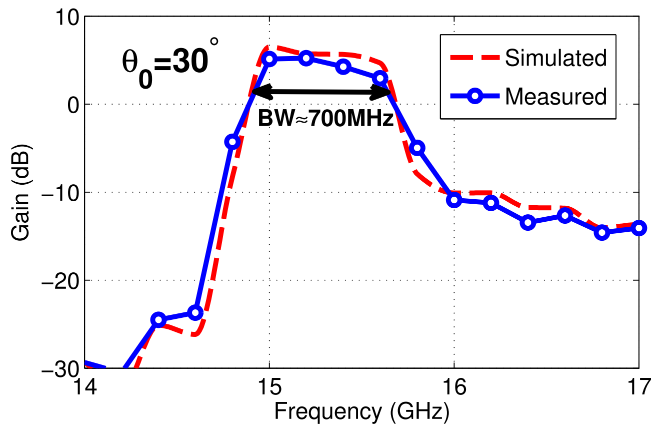


Fig. 8. Measured bandpass filtering response at a fixed observation angle $\theta_0 = 30^\circ$ for a BB-LWA with nulls.

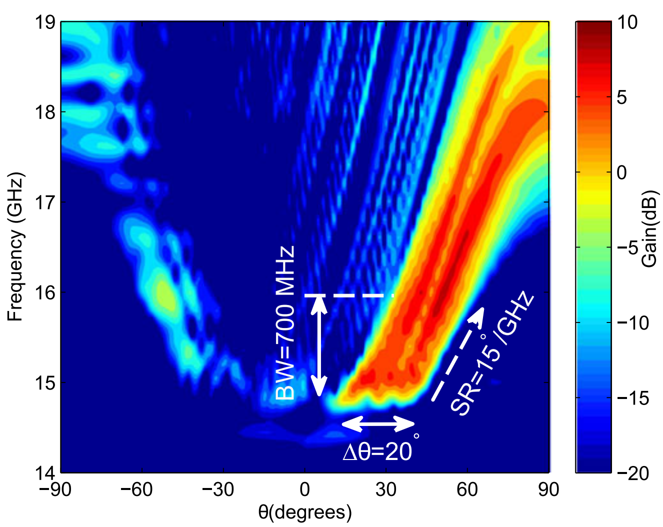


Fig. 9. Measured angular bandpass filtering performance for the BB-with-nulls LWA, where gain is represented by an intensity colorbar, θ is in x-axis, and frequency is in y-axis.

level of the main beam and its associated beamwidth strongly vary as frequency is shifted from the design frequency of 15 GHz (see Fig. 7). Also, this nonlinear response makes that the ripple observed in the angular domain (see Fig. 5) does not necessarily create ripples on the frequency domain, as it can be seen by the flat bandpass response in Fig. 8. When compared to FSS-based angular bandpass filters that allow for an independent synthesis of frequency and angular responses [8], the proposed leaky-wave SIW device lacks design flexibility. Nevertheless, this is due to its much simpler and integrated nature, which provides angular and frequency filtering from a single planar radiator.

Finally, the simultaneous angular bandpass filtering functionality is illustrated in Fig. 9, which represents the measured gain versus frequency (y-axis) and angle (x-axis). This type of plot visually relates the dependence between the aforementioned beamwidth $\Delta\theta$, scanning ratio SR, and resulting bandwidth BW. It is observed how the 20°-broad main beam moves toward 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 $-\theta_{\mathrm{RAD}}$, created by the antenna end discontinuity. However, the measured level of the reflected lobe is 10 dB below the main beam for all frequencies (see also Fig. 7).

IV. Conclusion

In this letter, 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 has been demonstrated for the first time. Measured results on fabricated $20\lambda_0$-long prototypes operating at 15 GHz with 20° BB have shown an increase in the angular rejection from 1 to 2.5 dB/° thanks to the addition of radiation null specifications. Finally, the performance as a planar-integrated angular bandpass filter in the [14 GHz, 19 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.

Acknowledgment

The authors would like to thank the firm Trackwise for manufacturing the SIW prototypes used in this work.

References

[1] I. Ohtera, "Diverging/focusing of electromagnetic waves by utilizing the curved leakywave structure: Application to broad-beam antenna for radiating within specified wide-angle," *IEEE Trans. Antennas Propag.*, vol. 47, no. 9, pp. 1470–1475, Sep. 1999.

[2] I. Ohtera, "On a forming of cosecant square beam using a curved leaky-wave structure," *IEEE Trans. Antennas Propag.*, vol. 49, no. 6, pp. 1004–1006, Jun. 2001.

[3] P. Burghignoli, F. Frezza, A. Galli, and G. Schettini, "Synthesis of broad-beam patterns through leaky-wave antennas with rectilinear geometry," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 136–139, 2003.

[4] J. L. Gomez-Tornero, A. J. Martinez-Ros, and R. Verdu-Monedero, "FFT synthesis of radiation patterns with wide nulls using tapered leaky-wave antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 518–521, 2010.

[5] A. J. Martinez-Ros, J. L. Gomez-Tornero, and G. Goussetis, "Holographic pattern synthesis with modulated substrate integrated waveguide line-source leaky-wave antennas," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3466–3474, Jul. 2013.

[6] R. Mailloux, "Synthesis of spatial filters with Chebyshev characteristics," *IEEE Trans. Antennas Propag.*, vol. AP-24, no. 2, pp. 174–181, Mar. 1976.

[7] P. Franchi and R. Mailloux, "Theoretical and experimental study of metal grid angular filters for sidelobe suppression," *IEEE Trans. Antennas Propag.*, vol. AP-31, no. 3, pp. 445–450, May 1983.

[8] D. Kinowski, M. Guglielmi, and A. Roederer, "Angular bandpass filters: An alternative viewpoint gives improved design flexibility," *IEEE Trans. Antennas Propag.*, vol. 43, no. 4, pp. 390–395, Apr. 1995.

[9] Y. J. Lee, J. Yeo, R. Mittra, and W. S. Park, "Application of electromagnetic bandgap (EBG) superstrates with controllable defects for a class of patch antennas as spatial angular filters," *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 224–235, Jan. 2005.

[10] F. Bayatpur and K. Sarabandi, "Miniaturized FSS and patch antenna array coupling for angle-independent, high-order spatial filtering," *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 2, pp. 79–81, Feb. 2010.

[11] K. Wu, "Multi-dimensional and multi-functional substrate integrated waveguide antennas and arrays for GHz and THz applications: An emerging disruptive technology," in *Proc. 7th Eur. Conf. Antennas Propag.*, Apr. 2013, pp. 11–15.

[12] J. L. Gomez-Tornero, A. Weily, and Y. Guo, "Rectilinear leaky-wave antennas with broad beam patterns using hybrid printed-circuit waveguides," *IEEE Trans. Antennas Propag.*, vol. 59, no. 11, pp. 3999–4007, Nov. 2011.

[13] A. J. Martinez-Ros, J. L. Gomez-Tornero, and G. Goussetis, "Planar leaky-wave antenna with flexible control of the complex propagation constant," *IEEE Trans. Antennas Propag.*, vol. 60, no. 3, pp. 1625–1630, Mar. 2012.