4 | CONCLUSIONS

A compact uniplanar MIMO antenna with band-notched characteristic has been designed for UWB applications. A compact size of 33 × 26 mm^2 is obtained with the help of a half circle-slot antenna structure. The back-to-back placement and a rectangular slot on the ground are employed to achieve a good port isolation. The measured results show that the proposed antenna obtains an impedance bandwidth varying from 3 to 11 GHz except rejection band of 4.5–5.5 GHz and the port isolation of less than −15 dB is also received. In addition, the acceptable gain and omnidirectional radiation pattern and the ECC of less than 0.03 are also realized. The measurements above prove that the proposed antenna is a good candidate for UWB MIMO applications.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (No. 61372001).

REFERENCES

[1] Nouri A, DadashZadeh GR. A compact UWB band-notched printed monopole antenna with defected ground structure. *IEEE Antennas Wirel Propag Lett.* 2011;10:1178–1181. vol

[2] Chuang C-T, Lin T-J, Chung S-J. A band-notched UWB monopole antenna with high notch-band-edge selectivity. *IEEE Trans Antennas Propag.* 2012;60(10):4492–4499.

[3] Siddiqui JY, Saha C, Antar YMM. Compact SRR loaded UWB circular monopole antenna with frequency notch characteristics. *IEEE Trans Antennas Propag.* 2014;62(8):4015–4020.

[4] Aghdam SA. A novel UWB monopole antenna with tunable notched behavior using varactor diode. *IEEE Antennas Wirel Propag Lett.* 2014;13:1243–1246. vol

[5] Liu X-L, Wang Z-D, Yin Y-Z, Ren J, Wu J-J. A compact ultra-wideband MIMO antenna using qsca for high isolation. *IEEE Antennas Wirel Propag Lett.* 2014;13:1497–1500. vol

[6] Li L, Cheung SW, Yuk TI. Compact MIMO antenna for portable devices in UWB applications. *IEEE Trans Antennas Propag.* 2013;61(8):4257–4264.

[7] Jian R;W, Hu Y, Yin R. Fan Compact printed MIMO antenna for UWB applications. *IEEE Antennas Wirel Propag Lett.* 2014;13:1517–1520.

[8] Zhang S, Pedersen GF. Mutual coupling reduction for UWB MIMO antennas with a wideband neutralization line. *IEEE Antennas Wirel Propag Lett.* 2016;15:166–169.

[9] Shuai Z, Ying Z, Xiong J, He S. Ultrawideband MIMO/diversity antennas with a tree-like structure to enhance wideband isolation. *IEEE Antennas Wirel Propag Lett.* 2009;8:1279–1282.

[10] Yingsong L;. W X, Li C, Liu T. Jiang. Two UWB-MIMO antennas with high isolation using sleeve coupled stepped impedance resonators. Antennas and Propagation (APCAP), 2012 IEEE Asia-Pacific Conference; August 2012, pp. 21–22, 27–29

[11] Kang L, Li H, Wang X, Shi X. Compact offset microstrip-fed MIMO antenna for band-notched UWB applications. *IEEE Antennas Wirel Propag Lett.* 2015;14:1754–1757.

[12] Peng G;S, He X, Wei Z, Xu N, Wang Y. Zheng Compact printed UWB diversity slot antenna with 5.5-GHz band-notched characteristics. *IEEE Antennas Wirel Propag Lett.* 2014;13:376–379.

[13] Tripathi S, Mohan A, Yadav S. A compact octagonal shaped fractal UWB MIMO antenna with 5.5 GHz band-notch characteristics. *Microwave RF Conference (IMaRC), 2014 IEEE International;* December 15–17, 2014, Vol. 181, pp. 178.

[14] Kun-Hui L, L-T, Hwang C-Y, Hsu S-M, Wang F-S. Chang. A compact printed UWB MIMO antenna with a 5.8 GHz band notch. Antennas and Propagation (ISAP), 2014 International Symposium on 2–5 December, 2014, pp. 419–420.

[15] Mei S;Y, Ping Zhang, Lu Y. Miniaturization of planar monopole antenna for ultrawideband radios. *IEEE Trans Antennas Propag.* 2010;58(7):2420–2425.

[16] Lu G, Wang SY, Gao X, Chen, Parini C. Miniaturisation of Printed Disc UWB Monopoles. Antenna Technology: Small Antennas and Novel Metamaterials, 2008. iWAT 2008. International Workshop on 4–6 March, 2008, pp. 95, 98.

[17] Gao G-P, Hu B, Zhang J-S. Design of a miniaturization printed circular-slot UWB antenna by the half-cutting method. *IEEE Antennas Wirel Propag Lett.* 2013;12:567–570. vol

[18] Blanch S, Romeu J, Corbella I. Exact representation of antenna system diversity performance from input parameter description. *Electron Lett.* 2003;39:705–707.

How to cite this article: Liu G, Liu Y, Gong S. Compact uniplanar UWB MIMO antenna with band-notched characteristic. *Microw Opt Technol Lett*. 2017;59:2207–2212. https://doi.org/10.1002/mop.30700

Received: 23 January 2017

DOI: 10.1002/mop.30706

Multilayered multiconductor stripline resonator and its application to bandpass filter with wide stopband

B. A. Belyaev[1,3] | A. M. Serzhantov[2] | A. A. Leksikov[1,3] | Y. F. Bal'va[1,3] | A. A. Leksikov[1,3]

[1] Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, Russia

[2]Institute of Engineering Physics and Radio Electronics, Siberian Federal University, Krasnoyarsk, Russia

[3]Reshetnev Siberian State Aerospace University, Krasnoyarsk, Russia

Correspondence
Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, Russia.
Email: a.a.leksikov@gmail.com

Abstract

A multilayered, multi-conductor stripline resonator is proposed. It is shown that increase in the number of conductors leads to increase the unloaded Q-factor and decrease the resonant frequency, with increasing the effects for thinner dielectric interlayer. Application of the resonator to the bandpass filter enables designing bandpass filters with very wide and deep stopbands. To prove this, a 4-pole bandpass filter, having central frequency 360 MHz and an overall size of 15.5 × 31.75 × 8.45 mm^3, was designed and fabricated.

KEYWORDS

bandpass filter, multi-conductor resonator, stripline resonator, wide stopband

1 | INTRODUCTION

A widespread use of wireless engineering in modern commercial and residential communication systems leads to considerable contamination of the air with spurious signals. To meet this challenge, in the last few decades, the need for filtering these signals has been steadily growing. It needs to be stressed here that the filter to be considered for such a use must be compact and cause low insertion loss. To simplify a communication system, and thus to reduce its cost, a new generation of bandpass filter that has wide stopband with maximum possible depth would be required. Three types of such a filter can be singled out in this regard. The first type is a microstrip filter, based on quarter-wave stepped-impedance resonator.[1–3] Such a filter is easy to fabricate and tune after fabrication; however, it is rather large in size and its stopband may extend to 5–7f_0 (f_0 is a central frequency of a filter) at level −40…–50 dB. The second type, LTCC filter,[4,5] is the most compact filter at the moment, but its stopband is rather shallow, limited by level −30…–40 dB, and width less than 5f_0. The third type is the multilayered stripline filter.[6,7] It is sufficiently compact in comparison to the microstrip filters; it causes much less insertion loss and the width of its stopband is roughly the same as that of the microstrip filter.

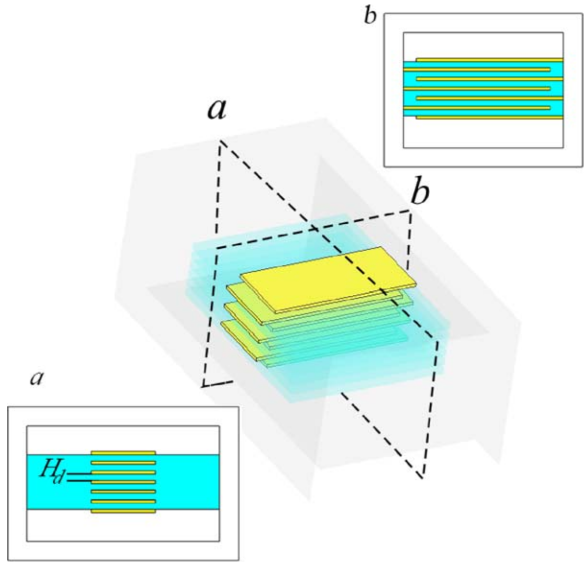

FIGURE 1 3D model of the resonator; and its cross-sections along *a, b* planes. [Color figure can be viewed at wileyonlinelibrary.com]

In this letter, we develop an idea of multi-conductor resonator that can be implemented in a multilayered structure. The idea of 2-layered structure was presented by several groups nearly the same time.[8–10] Earlier,[11] we proposed a 3-layered stripline resonator, which enables designing and fabricating a 6-pole filter that has 10.7f_0 stopband with 100 dB depth. Later, a multi-conductor microstrip resonator[12] was proposed that has sufficiently higher *Q*-factor in comparison to that of other compact microstrip resonators. These two types of resonator are physically very similar, and, therefore, it follows that the resonator's performance can be improved by increasing the number of conductors in the structure. It thus appears possible to achieve a very compact resonator having high unloaded *Q*-factor and an ability to create bandpass filters with very wide and deep stopband. In Section 2, we present a multi-conductor resonator, based on a multilayered stripline structure and discuss how geometric parameters influence the resonator's performance. Section 3 presents the 7-layer conductor resonator and 4-pole bandpass filter with 10% bandwidth, based on the resonator designed and fabricated for this work.

2 | STRIPLINE MULTI-CONDUCTOR RESONATOR

The structure of the resonator is presented in Figure 1. It consists of a multilayered metal-dielectric structure, suspended in the middle of a metallic case. The metal strip conductors are separated by thin dielectric layers (interlayers) and electromagnetically connected with each other. The conductors with odd numbers are short-circuited at one edge of the structure and those with the even numbers, at the opposite edge.

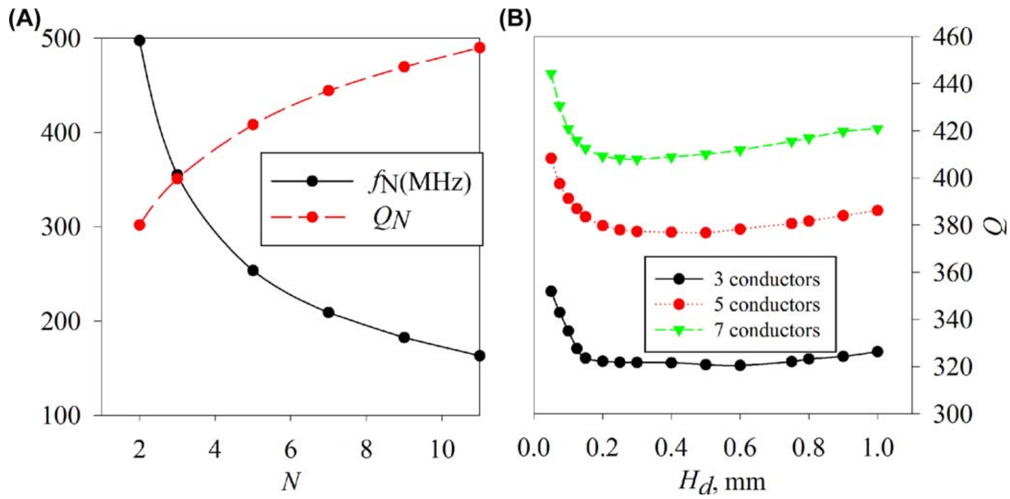

FIGURE 2 (A) Dependence of resonant frequency (solid line) and unloaded Q-factor versus number of conductors (dashed line) in the structure; (B) Dependence of Q-factor vs. thickness of dielectric layers in the structure. [Color figure can be viewed at wileyonlinelibrary.com]

Each conductor in the structure can be considered a quarter-wave resonator. When the thickness of dielectric interlayer is very small, as compared to the distance between the conductors and the upper and bottom walls of the case, the electromagnetic coupling between them is very strong and mainly inductive. High-frequency currents of the lowest-frequency mode f_1 flow along the conductors in the same direction, while the voltage on the adjacent conductors has different signs. This results in the summation of the inductive and capacitive couplings and consequent significant repulsion of the eigenfrequencies of the resonator that leads to a significant lowering of the first-mode frequency.

This fact can be proved by the dependencies of a resonant frequency and the unloaded Q-factor versus the number of conductors in the resonator, presented in Figure 2A. The dependencies were obtained by simulation, using AWR Microwave Office. Fifty micrometer of dielectric layers having $\varepsilon = 3.5$ and $\tan\delta = 0.001$ were chosen as the base for copper-strip resonator of 2.5 mm width having 0.9 overlap

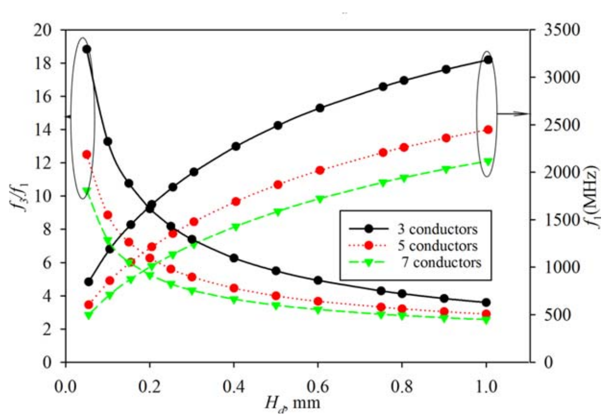

FIGURE 3 Dependence of resonant frequency and the ratio of the frequencies of the two lowest modes versus the thickness of dielectric layers in the structure. [Color figure can be viewed at wileyonlinelibrary.com]

with adjacent conductors. The distance between the multilayered structure and the walls was 4 mm. The resonators were tuned at 500 MHz for each number of conductors to determine their Q-factors. The length of the 2-layer resonator was 13 mm, while that of 11-layer was only 4.3 mm. One can see considerable similarity between the curves presented in Figure 2A and those obtained for multi-conductor microstrip resonator, described earlier.[12] So, for the resonator under investigation, we can use the same equivalent circuit and theory as those proposed for the microstrip. The unloaded quality factor of the lowest resonance and its frequency can, therefore, be estimated using the next expressions:

$$Q_N = \sqrt{\frac{N}{2}} Q_2, \quad f_N = \frac{1}{\sqrt{N/2}} f_2, \tag{1}$$

where Q_2 and f_2 denote respectively the unloaded Q-factor and resonant frequency of a two-conductor stripline resonator on the suspended substrate, and N the number of conductors in the structure. One can see from Equation (1) that the increase in the number of conductors in the structure results in the rise of the resonator's unloaded Q-factor and simultaneous lowering of its resonant frequency.

It is obvious that the mode of repulsion depends on the distance between the conductors and, thus, on the thickness of the interlayers. This repulsion reflects first in the ratio of the frequencies of the two first modes and, as a result, determines the width of stopband. Also, the Q-factor is influenced. Therefore, the behavior of Q-factor and the mode ratio vs. resonator structural parameters become important issues, especially for designing a filter. A simulation was performed for three structures having 3, 5, and 7 conductors in the resonator. The width and overlapping of the conductors chosen, as also the dielectric parameters of the interlayers, were the same as those of the conductors used earlier. For each structure, the resonator was excited, using the

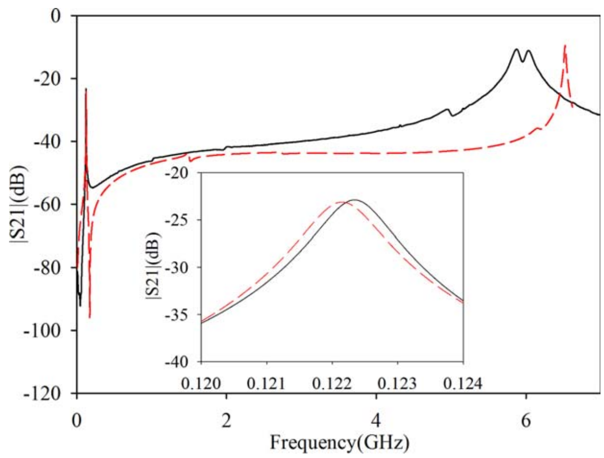

FIGURE 4 Frequency response of the fabricated resonator (solid line) in comparison with that of the simulated resonator (dashed line). [Color figure can be viewed at wileyonlinelibrary.com]

inductive coupling with the central conductor of the resonator. This renders the coupling of the resonator with the feedlines week enough for estimating the unloaded Q-factor, and suppressing the resonator's second mode. The results, presented in Figure 2B, show that the Q-factor increased by 26%, with increase in the number of conductors in the resonator, and 10% with simultaneous decrease in the thickness of the interlayers and in the length of the resonator (4.1 times for 3-conductor structure, 4.4 times—5 conductors and 4.7 times—7 conductors). Moreover, when the thickness of the interlayers decreased to 0.2 mm and less, a significant change was observed in the Q-factor.

In Figure 3, the results for the first oscillation mode and the ratio of the two first modes' frequencies are presented. Analysis of these results shows that, with increase in the number of conductors, the dependence of the 1st mode frequency on the interlayer thickness became stronger. For example, the change in interlayer thickness from 1 mm to 0.05 mm of a 3-conductor structure led to 3.8 times change in the frequency (from 3182 to 846 MHz), 4 times for 5 conductor structure, and 4.2 times for 7 conductor structure. Finally, a 7 conductor resonator with 0.05 mm thickness of the interlayer will be 7.1 times shorter and will have a Q-factor that is 36% higher than that of the 3 conductor resonator with 1 mm-thick interlayer. However, it was found that increase in the number of conductors decreased the ratio of the frequencies of the two first modes (Figure 3); the maximum ratio for 3-conductor structure was found to be 18.4 and that for 7-conductor structure only 10.4.

3 | 4-POLE BANDPASS FILTER

A 7-conductor resonator and a 4-pole bandpass filter on its base, having 10% fractional bandwidth were designed and fabricated to prove the results of the simulation. A 50 μm polyamide tape, having loss tangent 0.008, was used as the interlayer in the experiment. The fabricated resonator (its frequency response is presented in Figure 4) had the 1-st resonant frequency $f_0 = 122.5$ MHz and size $5 \times 18.5 \times 8.05$ mm^3. The measured unloaded Q-factor was found to be only 112, obviously because of very high tangent loss, but it is in good agreement with the simulation result ($Q = 115$).

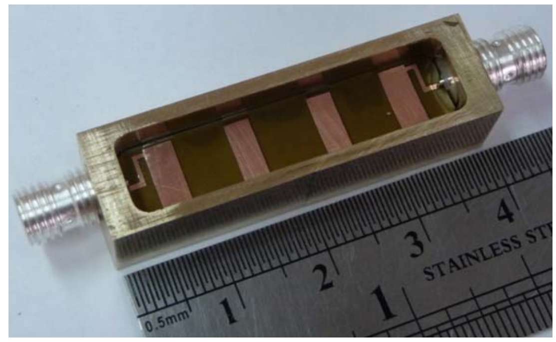

FIGURE 5 Photograph of the fabricated filter. [Color figure can be viewed at wileyonlinelibrary.com]

The 4-pole filter (Figure 5) fabricated and tuned to central frequency 360 MHz had an overall size of $15.5 \times 31.75 \times 8.45$ mm^3. The topology parameters were as follows: length of the resonators $l = 15.5$ mm; the overlap between conductors was 0.97 and the width of the conductors $w = 2.5$ mm. The gap between the inner resonators was 5.75 mm and that between inner and outer resonators 5 mm. A galvanic connection of the top conductors of the external resonators to the feedlines was chosen to create an optimum match.

The comparison of the frequency responses obtained for the simulated and fabricated filters in the wide band is shown in Figure 6 and that in the narrow band in the inset of the same figure. The fabricated filter had minimum in-band insertion loss of 2.5 dB and maximum return loss of 11 dB. One can see a good agreement between the results of simulation

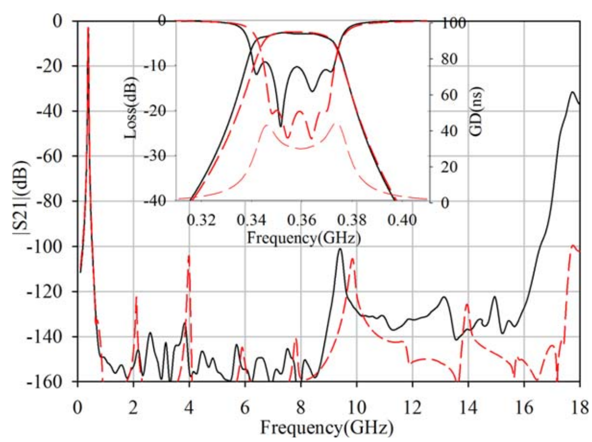

FIGURE 6 Comparison of the frequency responses of the fabricated filter (solid line) with that of the simulation (dashed line). [Color figure can be viewed at wileyonlinelibrary.com]

and experiment. The measured stopband of the filter was found to be 60 dB up to $44f_0$ and 110 dB up to $24f_0$.

4 | SUMMARY

This letter has described an investigation of a multilayered, multi-conductor stripline resonator, which consists of metal-dielectric structure suspended in the middle of a metallic case. All the conductors in the resonator have strong mutual inductive coupling, and hence the previously proposed theory for interdigital microstrip resonator can be incorporated. Increase in the number of the conductors leads to raising the unloaded Q-factor and lowering the resonant frequency; moreover, with tinier interlayers, the effects magnify.

A 4-pole passband filter was designed and fabricated, based on the resonator. It was found that, for the central frequency of 360 MHz and 10% fractional bandwidth, the overall size of the filter was only $15.5 \times 31.75 \times 8.45$ mm^3 ($0.019\lambda \times 0.038\lambda \times 0.013\lambda$). The fabricated filter has upper stopband up to $44f_0$ at level −60 dB and $24f_0$ at level −110 dB.

REFERENCES

[1] Deng H-W, Zhao Y-J, Chen W, Liu B, Liu Y-Y. Wide upper-stopband microstrip bandpass filter with dual-mode open loop stepped-impedance resonator and source-load coupling structure. *Microw Opt Technol Lett.* 2012;54:1618–1621.

[2] Kim CH, Chang K. Wide-stopband bandpass filters using asymmetric stepped-impedance resonators. *IEEE Microw Compon Lett.* 2013;23(2):69–71.

[3] Huang T, Shao ZH, Huang YM. Size-miniaturized and selectivity enhanced bandpass filter using folded stepped-impedance resonators. *Microw Opt Technol Lett.* 2017;59:60–62.

[4] Deng J, Wang B-Z, Gan T. Compact LTCC bandpass filter design with controllable transmission zeros in the stopband. *Microw Opt Technol Lett.* 2006;48:2261–2264.

[5] TamuraYang M, Itoh TT. Very compact and low-profile LTCC unbalanced-to-balanced filters with hybrid resonators. *IEEE Trans Microw Theory Tech.* 2011;59(8):1925–1936.

[6] Hepburn L, Hong J. Compact integrated lumped element LCP filter. *IEEE Microw Compon Lett.* 2016;26(1):19–21.

[7] Mengkui S, Shao Z, Jiang You C, Ban F. Ku-band compact bandpass filter with wide upper stopband using multilayer liquid crystal polymer technology. *Microwave Opt Technol Lett.* 2014;57:1121–1125.

[8] Belyaev BA, Leksikov AA, Tyurnev VV, Kazakov AV. Stripline filter with suspended substrate. Transactions of 15th International Conference "Microwave &Telecommunication Technology"; 2005, pp. 506–507.

[9] Yunchi Z, Zaki KA. Compact, coupled strip-line broad-band bandpass filters. IEEE MTT-S International Microwave Symposium Digest (2006), pp. 1189–1192.

[10] Yong-Sheng D, Zhou W-K, and, et.al. Design and implementation of an miniaturized LTCC filter with high stopband rejection. 2010 International Conference on Microwave and Millimeter Wave Technology (2010), pp. 1584–1587.

[11] Belyaev BA, Serzhantov AM, Tyurnev VV, Leksikov AA, Bal'va YF. Stripline bandpass filter with wide stopband and rejection level up to 100 dB. *Microw Opt Technol Lett.* 2013;55:2866–2869.

[12] Belyaev BA, Serzhantov AM, Leksikov AA, Bal'va YF, Leksikov AA. Novel high-quality compact microstrip resonator and its application to bandpass filter. *IEEE Microw Compon Lett.* 2015;25(9):579–581.

How to cite this article: Belyaev BA, Serzhantov AM, Leksikov AA, Bal'va YF, Leksikov AA. Multilayered multiconductor stripline resonator and its application to bandpass filter with wide stopband. *Microw Opt Technol Lett*. 2017;59:2212–2216. https://doi.org/10.1002/mop.30706

Received: 24 January 2017

DOI: 10.1002/mop.30711

H-plane corporate waveguide-fed 4-aperture-stacked circular microstrip patch linear array for Ku band applications

A. T. Muriel-Barrado | **J. L. Masa-Campos** | **P. Sanchez-Olivares**

Group of RadioFrequency: Circuits, Antennas & Systems, Department of Electronics and Communication Technology, Autonoma University of Madrid, Madrid 28049, Spain

Correspondence
José Luis Masa-Campos, Group of RadioFrequency: Circuits, Antennas & Systems, Department of Electronics and Communication Technology, Autonoma University of Madrid, Ciudad Universitaria de Cantoblanco, Ctra. de Colmenar Viejo, km 15, Cantoblanco, 28049 Madrid.
Email: joseluis.masa@uam.es

Funding information
Spanish Government, Ministry of Economy, National Program of Research, Development and Innovation, TECOAMP (EC2013-47106-C3-2-R), ENABLING5G (TEC2014-55735-C3-1-R), ADDMATE (TEC2016-76070-C3-1-R), and SPADERADAR-CM (S2013/ICE-3000) from Madrid Region Government.

Abstract
In this article, a linearly polarized 4-element linear array in Ku band is presented. The single element consists of a circular microstrip patch capacitively coupled to a printed