Inkjet-Printed Bandstop Filters for Interference Suppression in Multi-Standard Wireless Systems

Olukoya, O. and Budimir, D.

This is a copy of the author's accepted version of a paper subsequently published in the proceedings of the *IEEE Asia Pacific Microwave Conference (APMC2016),* New Delhi, India, 05 to 09 Dec 2016.

It is available online at:

https://dx.doi.org/10.1109/APMC.2016.7931399

Proceedings of the Asia-Pacific Microwave Conference 2016

Inkjet-Printed Bandstop Filters for Interference Suppression in Multi-Standard Wireless Systems

Oludotun Olukoya [1], Djuradj Budimir [2]
Wireless Communications Research Group, University of Westminster, 115 New Cavendish Street, London, W1W 6UW, United Kingdom
[1] *oludotun.olukoya@my.westminster.ac.uk*
[2] *d.budimir@westminster.ac.uk*

***Abstract*- This paper presents a highly compact inkjet printed microstrip bandstop filter (BSF) for interference suppression in multi-standard wireless applications. The structure is designed with strict specifications for inkjet printing such as the use of the Kapton substrate and its flexible polyimide film. The design was simulated based on Kapton substrate with a thickness of 50µm and dielectric constant of 3.4. The simulated results show a good narrowband response with good stopband attenuation of about 38 dB. When compared to other published BSFs, the proposed structure occupies the least normalized area and best return loss performance up to 10 GHz. This filter is then used to reject interference in a multi-standard wireless transmitter system with suppression of about 30 dB achieved with a great level of noise and spurious response reduction thereby improving the overall performance of the system. This type of filter will be very useful to eliminate undesired signals in next generation 4G LTE-Advanced and 5G mobile networks as well as being very attractive for modern day multi-standard wireless applications such as machine to machine (M2M) communications and internet of things (IoT).**

I. INTRODUCTION

With the rapid emergence of printed electronics, Inkjet printing technology is becoming more prominent due to merits such as reduction in manufacturing costs, shorter fabrication time and aiding mass production flexibility [1]. Inkjet printing makes use of nanoparticle inks rather than conventional copper used in traditional techniques permitting the use of flexible substrates. Inkjet printing is preferred to conventional etching techniques owing to its adoption of low cost processes such as the additive measures. The actual droplet is deposited only where it is needed reducing material usage and waste, making it more energy conservative and environmentally friendly [2].

A couple of RF/Microwave/mm-wave components and systems attributed to inkjet printing using different specific substrates have emerged in recent years. For instance, paper is an acceptable substrate used more often in the past decade due to its low cost and simplicity [3] but with high frequency absorption drawbacks and a range of humidity issues such as moisture absorption [4]. Due to this, other substrates have emanated such as Injected Printed Humidity Sensor on Kapton Substrate [5], Flexible Microwave filter on Liquid Crystal Polymer (LCP) Substrate [6] and LPDA antenna on PET (Polyethylene terephthalate) Substrate [7].

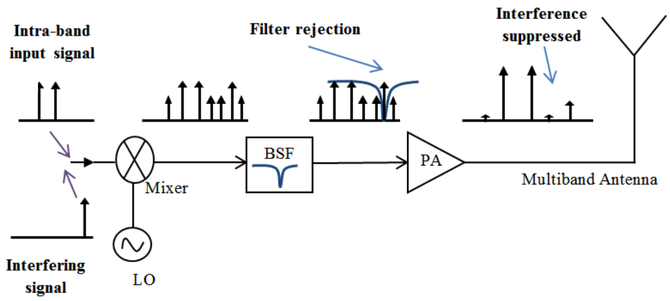

Figure 1. Block diagram of the wireless transmitter system for the application of the proposed BSF.

With the advancement of flexible electronics, and the push for low cost and efficiency, the flexible materials used for applications with ever keen interest such as wireless, cognitive radio and other high frequency applications have been critically investigated [6]. The flexible Kapton polyimide film is considered in this paper because it is durable and maintains electrical and physical properties over a wide temperature range withstanding high temperature levels making it attractive for modern applications such as internet of things [5].

A novel BSF design using Kapton substrate and its flexible polyimide film for inkjet printing is presented. The designed filter is very compact with reduced size and good stopband response characteristics when compared to other published BSFs.

Furthermore, the designed filter is also implemented in a Multi-standard wireless transmitter system. One of the main challenges facing the next generation networks is high data transmission and spectrum availability. Carrier aggregation (CA) is one of the techniques peculiar to LTE-Advanced (Long Term Evolution) used by network operators to maximize spectrum availability, improve capacity and network performance, but with increasing levels of intra-band and inter-band interference [8].

The BSF can be used to reject such kinds of interference using the technique in Fig. 1 above. The designed BSF was implemented in this paper and was able to effectively suppress interference in a Multi-band wireless transmitter system to improve performance and would be very useful for next generation networks such as 4G and 5G communication systems.

978-1-5090-1592-4/16/$31.00 ©2016 IEEE

II. FILTER DESIGN

The filter design should be compact with good selectivity and sufficient attenuation at cutoff frequency to reject interfering and unwanted signals and improve performance. The narrowband BSF design aims to reject wireless (Wi-Fi) interference at about 2.4 GHz in wireless transmitter architectures.

The BSF structure is a T-shaped stepped impedance microstrip configuration as shown in Fig. 2 below. Modifying the defects on the main transmission line, creates different stopband characteristics at different frequencies which aids miniaturization as larger dimensions would normally be required for lower frequencies in such designs.

Using Quasi-TEM approximation equations, the width (W) of the microstrip line, effective dielectric constant (ε_{eff}) and guided wavelength (λ_g) can be obtained using empirical expressions as shown in equations (1) – (3).

For this kind of filter design to achieve compactness, very thin conductors are used. Silver is the metal type chosen for compatibility with the silver nanoparticles used for inkjet printing. For such tiny conductor cases of thickness tending towards zero (such as t = 1 µm in this case), the expression for the effective dielectric constant is calculated in terms of the width W of the conducting strip of the microstrip line and the thickness (h) of the dielectric substrate. The relative expression for ε_{eff} is given in (1) below:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-1/2} \quad (1)$$

Where h is the thickness of the substrate and ε_r is the dielectric constant.

For the purpose of this design, the guided wavelength (λ_g) and electrical length (ℓ) (quarter wavelength) would be used to determine the actual dimensions of the different metal patterns to be used during the software design of the structure.

$$\lambda_g = \lambda_0 [\varepsilon_{eff}]^{-1/2} \quad (2)$$

$$\ell = \lambda_g / 4 \quad (3)$$

Where λ_0 (c/f_0) is the wavelength of free space.

At the resonant frequency (f_0) of the BSF, using equations (1) - (3), the required dimensions could be determined. However, to obtain better bandstop response from the simulations, the circuit had to be optimised. The two inverted T-shaped patches are used to vary stopband attenuation.

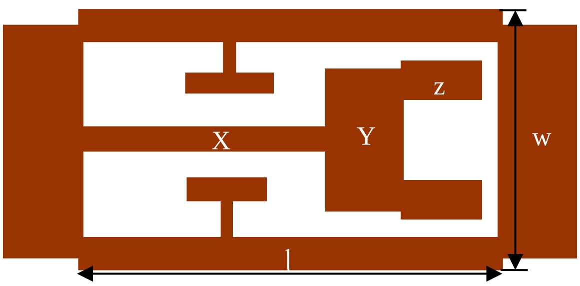

Figure 2. Structure of proposed bandstop filter

The final dimensions of the proposed circuit design as shown in Fig. 2 above are as follows: ℓ = 15mm, W = 0.11 mm, X = 14.98 mm by 0.01 mm, Y = 0.6 mm by 0.05 mm and Z = 0.005 mm by 0.39 mm.

III. RESULTS

The structure is designed on a 50 µm thick Kapton substrate of dielectric constant (ε_r) of 3.4 and loss tangent (tanδ) of 0.0021. Simulations are done using the *emSonnet* commercial software. The simulated results of designed filter are shown in Fig. 3.

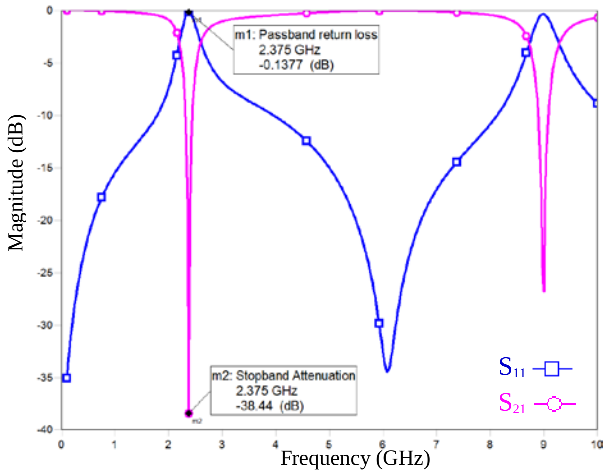

Figure 3. Interference Rejection at BSF cutoff frequency

The structure produces good stopband rejection (S_{21}) of -38.44 dB, fractional bandwidth (FBW) of 6.25% and Q-factor of 16 at the resonant frequency of 2.375 GHz with its passband less than -0.14 dB exhibiting a very low loss. Fig. 3 also presents excellent inter-band return loss performance properties (S_{11}> -30 dB up to 10 GHz).

The designed filter shows excellent bandstop properties such as attenuation and loss when compared to other filters as shown in Table I.

TABLE I

SIZE AND PERFORMANCE COMPARISM OF BSFS

(BSF)	Dielectric Constant (ε_r)	Substrate thickness (mm)	Normalized area (λ_g x λ_g) (mm*mm)	Return Loss S_{11}(dB)	Attenuation S_{21} (dB)
[9]	3.48	0.508	0.28*0.062	-	>-30
[10]	2.2	1.54	0.35*0.065	>-10	>-45
[11]	2.55	1.5	0.201*0.101	>-10	>-25
[12]	2.65	1.6	0.22*0.11	>-15	>-25
This work	3.4	0.05	0.27*0.002	>-30	>-35

The proposed bandstop structure has rectangular area of 15 mm x 0.11 mm. By using equations (1) – (3), the normalized area of other similar bandstop filter structures have been calculated and compared in Table I below. The presented structure occupies the smallest rectangular area and records the least normalized area (0.27 λ_g x 0.002 λ_g).

IV. BSF IMPLEMENTATION IN MULTI-STANDARD WIRELESS SYSTEMS

The designed BSF in section II and III above can be introduced into the wireless transmitter architecture. Fig. 4 shows the implementation of the BSF in a 4G wireless transmitter to investigate its rejection abilities.

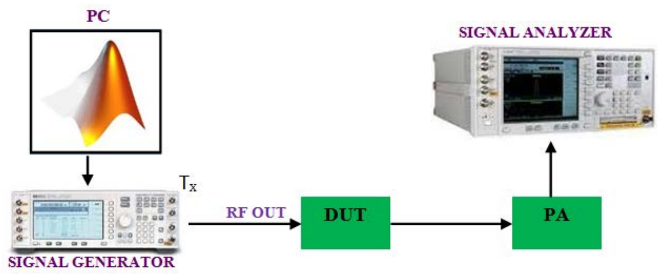

Figure 4. Bandstop filter implementation in a 4G wireless transmitter

A 3 MHz LTE signal is generated in the signal generator. The signal is modelled and measured results used in Agilent Keysight Signal Studio Kit. The DUT (Device under Test (BSF)) was fed by the 3 MHz LTE signal at the resonant frequency of the DUT (2.375 GHz). The signal passes through the DUT and then the Mini-circuits ZFL-PA. The results with and without the BSF could be seen in Fig. 5 below. The BSF has been able to successfully suppress interference above 30 dB. However, for the BSF implementation in this paper, placing the DUT before the PA is preferred as it ensures that interference is suppressed prior to amplification. Fig. 5 also shows the advantage of placing the DUT (BSF) at the input and output of the PA with the former giving a better overall output performance with good interference rejection abilities as well as increasing sensitivity and linearity as well.

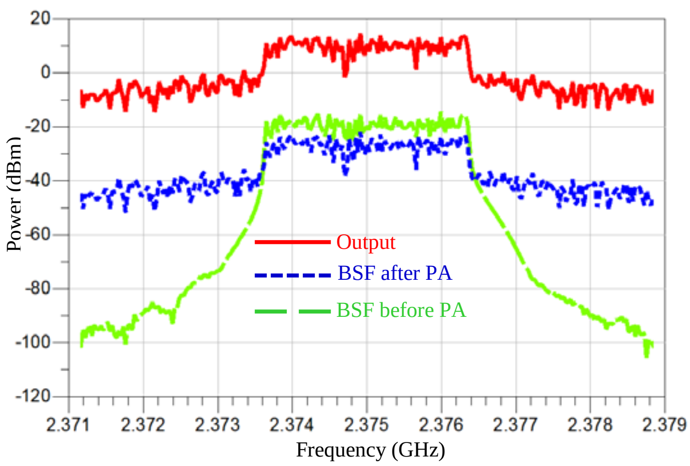

Figure 5. Interference Rejection at BSF cutoff frequency

Furthermore, the BSF can be used useful to suppress interference in next generation Multi-standard systems such as LTE-Advanced and 5G communication systems. LTE-A carrier aggregation is becoming very prominent as the quest for higher data speeds increase. One of its major challenges stems from reduced spectrum availability due to larger bandwidths applications. By aggregating carriers, higher data speeds could be achieved, but it comes at a cost of high levels of intra and inter-band interference. The BSF filter presented could be used to reject inter and intra-band interfering signals for such applications. Fig. 6 is the schematic for interference suppression with the BSF in such Multi-band wireless system.

In this test setup, two 3 MHz intra-band signals (f_1 and f_2) are transmitted along with a third interfering signal (f_{Int}) still using the multiband rejection technique described in Fig. 1. The designed BSF rejects the interfering signal (f_{Int}) which reduces the noise level at the input of the power amplifier. When the PA amplifies the signal at its input, it gives a better output performance and interference is seen to be attenuated effectively.

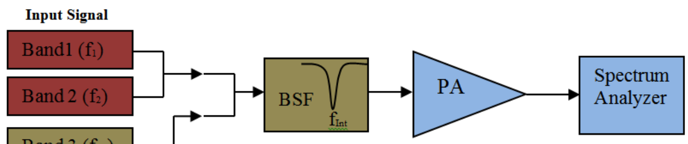

Figure 6. Block diagram of BSF implementation for the multi-standard transmitter system.

The effect of such interfering signal is shown in Fig. 7 whereby the interfering signal actually reduces the gain of the signal by over 3 dB but most importantly, adds unwanted spurious responses thereby leading to a high increase in noise levels which reduced the sensitivity of the system. This impacts the system performance negatively. Rejecting the interfering signal with the BSF restores the two intra-band signals (as shown between 2 and 2.3 GHz in Fig. 7) to its initial state without the interfering signal.

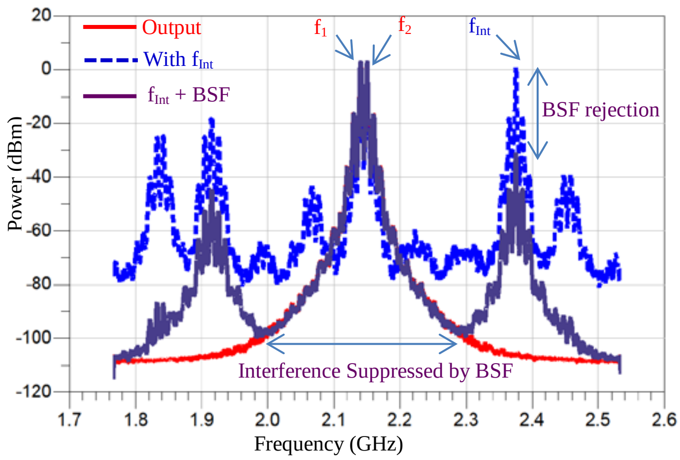

Figure 7. Multi-band Interference Suppression with BSF

The designed BSF has been able to reject the interfering signal (f_{Int}) by more than 30 dB and the effects of the interfering signal on the overall wireless transmitter system has been sufficiently suppressed thereby improving overall system sensitivity and performance.

V. CONCLUSIONS

A highly compact inkjet printed narrowband BSF has been successfully designed and analyzed in this paper. The presented BSF was not only able to achieve a reasonable size reduction but also exhibits good stopband characteristics. These characteristics include a narrow bandwidth, stopband attenuation of about 38.4 dB at resonant frequency of 2.375 GHz and an improvement in return loss (S11) performance up to 10 GHz. The designed BSF has been implemented in a Multi-standard wireless transmitter system to suppress the interference effects. In this technique, the BSF rejects interference prior to amplification achieving a better overall sensitivity and linearity performance than the case whereby it is used at the output of the PA. The BSF was successful in rejecting the interfering signal by about 30 dB whilst improving the sensitivity, linearity and improving the overall performance of Multi-standard wireless systems. This BSF is useful for suppression of various kinds of interference in LTE-Advanced networks and also attractive for next generation 5G networks along with some low power modern day applications such as internet of things (IoT) and machine to machine (M2M) communications.

REFERENCES

[1] H. Saghlatoon, L. Sydänheimo, L. Ukkonen, and M. Tentzeris, "Optimization of Inkjet Printing of Patch Antennas on Low-Cost Fibrous Substrates", *IEEE Antennas Wireless Propag. Lett.*, vol. 13, no. 1, pp. 915-918, May 2014.

[2] B. Ando, S. Baglio, C. O. Lombardo, and V. Marletta, "A Low-Cost Accelerometer Developed by Inkjet Printing Technology", IEEE *Trans. on Instrum. Meas.*, vol. 65, no. 5, pp. 1242-1248, May, 2016.

[3] R. Vyas, V. Lakafosis, A. Rida, N. Chaisilwattana, S. Travis. J. Pan and M. Tentzeris, "Paper-Based RFID-Enabled Wireless Platforms for Sensing Applications", *IEEE Trans. on Microwave Theory and Techniques*, vol.57, No.5, part 2, pp.1370-1382, May 2009.

[4] H. L. Kao, C. L. Cho, X. Dai, C. S. Yeh, X. Y. Zhang, L. C. Chang and H. C. Chiu, "Hairpin Bandpass Filter on Liquid Crystal Polymer Substrate using," *IEEE MTT -S Int. Microwave Sym, Seattle, W A*, pp. 1-4, June 2013.

[5] J. Virtanen, L. Ukkonen, T. Bjorninen, A. Z. Elsherbeni, and L. Sydänheimo, "Inkjet-printed humidity sensor for passive UHF RFID systems," *IEEE Trans. on Instrum. Meas*., vol. 60, no. 8, pp. 2768–2777, Aug. 2011.

[6] Y. Lan, Yuehang_Xu, C. Wang, Z. Wen, Y. Qiu, T. Mei, Y. Wu, and R. Xu, "Flexible Microwave filters on Ultra-Thin Liquid Crystal Polymer substrate", *IEEE MTT-S Int. Microw. Symp.*, Phoenix, Arisona, pp. 1-3, May 2015.

[7] G. A. Casula, G. Montisci, P. Maxia, G. Valente, A. Fanti and G. Mazzarella, "A Low-Cost Dual-Band CPW-Fed Printed LPDA for Wireless Communications", *IEEE Antennas Wireless Propag. Lett.*, vol. 15, no. 1, pp. 1333-1336, April 2016.

[8] S. Dimitrov, "Iterative Cancellation of Non-Linear Distortion Noise in Digital Communication Systems," *IEEE Transactions on Comm*., vol.63, no.6, pp.2325-2336, June 2015.

[9] W. Y. Sam, Z. Zakaria, M. A. Mutalib, M. F. M. Fadhli, A. R. Othman, and A. A .M. Isa, "A Compact DMS Triple-Band Bandstop Filter with U-slots for Communication Systems", *Proc. IEEE Int. Conf. on Electronic Design*, Penang, Malaysia, pp. 383-386, August 2014.

[10] K. Chakrabarty, and D. Budimir, "Compact tunable bandstp filters using Defected Microstrip Structure for multi-standard wireless systems", *Proc. 43rd Eur. Microw. Conf.*, Nuremberg, Germany, pp. 1031-1034, October 2013.

[11] J. Wang, H. Ning, L. Mao, and M. Li, "Miniaturized Dual-Band Bandstop Filter Using defected Microstrip Structure and Defected Ground Structure", *IEEE-MTT-S Int. Microw. Symp. Dig.*, Montreal, Canada, pp. 1-3, June 2012.

[12] D. La, Y. Lu, and S. Sun, "Novel Bandstop Filter Using Dual-U Shape Defected Microstrip Structure", *Proc. Int. Symp. Signals, Systems and Electronics*, Nanjing, China, pp. 400-402, September 2010.