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Research Article

A Suspended Stripline Frequency Tripler Using a Left-Handed Nonlinear Transmission Line

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A suspended stripline frequency tripler using a left-handed nonlinear transmission line (LH NLTL) is presented. The proposed tripler using the LH NLTL is composed of a series of varactor diodes, shunt inductances, and a high-pass filter implemented with suspended stripline (SSL). An ultrawideband microstrip-to-suspended stripline transition is also utilized. The fabricated LH NLTL provides the minimum insertion loss of 1.7 dB and the maximum insertion loss of 4.7 dB for a wide frequency band from 2.6 to 18 GHz. As a tripler, the measured minimum third harmonic conversion loss is 15.3 dB at an input frequency of 2.4 GHz and typically 17 dB from 2 to 3.1 GHz.

1. Introduction

The frequency multipliers are often used as important components to obtain low phase noise microwave/millimeter-wave sources. High frequency signal sources can be obtained by multiplying the low frequency signal. Generally, the frequency multiplier uses either transistors or diodes as a nonlinear element. FET multipliers usually have trade-off between bandwidth and conversion loss [1]. Varactor diodes multipliers are naturally narrowband [2]. However, varactor diode-based frequency multipliers, in general, generate very little noise (phase as well as amplitude noises). The only noise source in this type of multipliers is thermal noise, which comes from the series resistance of the varactor.

Left-handed (LH) media, first postulated by Veselago [3], are becoming an exciting reality, particularly as they are being demonstrated in resonant radio frequency and microwave circuits [4, 5]. In [6], the authors presented a theoretical investigation of the basic nonlinear wave propagation phenomena in LH media, which is based on the duality of the conventional NLTL, that is, a LH NLTL with anomalous dispersion. They also proved theoretically that the third harmonic generation could be very effective in LH NLTL. The frequency multipliers based on LH NLTLs are typically compact since the length of the section in practice is determined by the diode package size. These triplers can also be low loss since fewer diodes are required to achieve the same value of conversion efficiency. The authors in [6], however, did not show the actual experimental results. In [7, 8], the authors presented the experimental results for the second harmonic generation in a short LH NLTL. Compared to the previous works [6–8], our work shows that the bandwidth of the LH NLTL is extended significantly with an adequate design using 3D simulation and careful fabrication and demonstrates that the third harmonic generation is very effective with LH NLTL.

In this paper, we present a suspended stripline tripler using a left-handed nonlinear transmission line (LH NLTL). The proposed tripler using the LH NLTL is composed of a series of varactor diodes, shunt inductances, and a high-pass filter, which were implemented with suspended striplines. Compared to the earlier literature regarding the triplers [9–11], our work shows a comparable performance with a smaller size, wider bandwidth, and a simpler structure. And, for the suspended stripline circuit, a suitable and high performing MS-to-SSL (microstrip line to suspended stripline) transition developed by the authors' group [12] has been utilized.

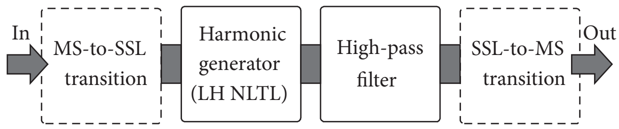
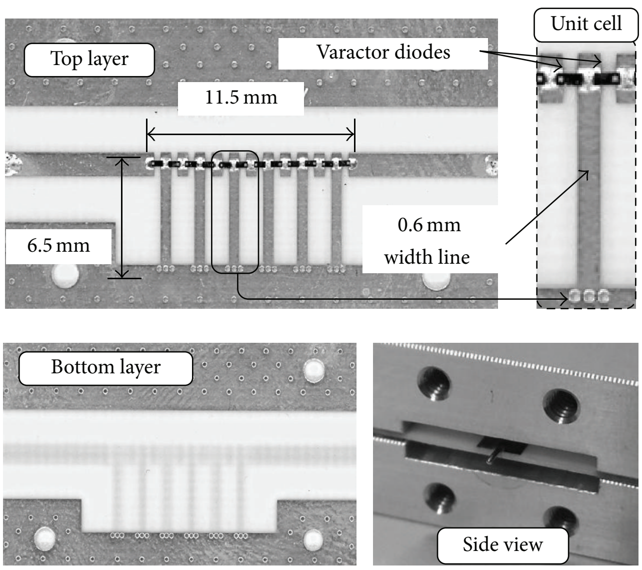
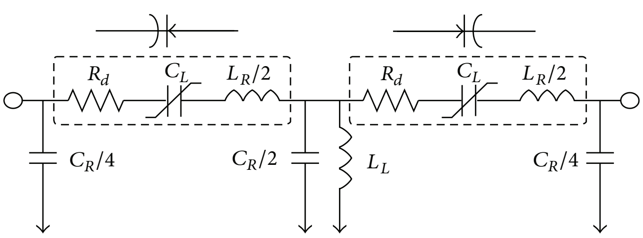


Figure 1: Block diagram of the proposed tripler.



(a)



(b)

Figure 2: (a) Fabricated third harmonic generator using LH NLTL. (b) Equivalent circuit of a unit cell.

2. Design of the Balun and Antenna

The proposed tripler is composed of a harmonic generator, a high-pass filter, and MS-to-SSL transitions as shown in Figure 1. The harmonic generator utilizes nonlinear characteristics of the LH NLTL. The proposed LH NLTL has a simple structure but provides a wide left-handed passband. To effectively remove harmonics, a suspended stripline 5th-order high-pass filter is added. MS-to-SSL transitions are used at the input and output sides to easily integrate with microstrip circuits.

2.1. Third Harmonic Generator Design. Figure 2(a) shows the picture of the proposed suspended stripline third harmonic generator using six-section LH NLTLs. In this paper, for the suspended stripline structures, the circuit was realized on a Rogers RO4003 substrate with $\varepsilon_r = 3.8$, thickness $h = 0.3$ mm, and cover height of $h_c = 0.5$ mm. The fabricated harmonic generator circuit is 11.5 mm by 6.5 mm in size except for the connectors and extra space for the measurement. A row of 0.6 mm by 1.4 mm copper pads separated by 0.2 mm gaps is formed on the surface of substrate. The twelve varactor diodes (M/A-COM MA46H120 hyperabrupt junction GaAs flip-chip) are attached between these pads. The junction capacitance (C_{j0}) of the diodes, from the manufacturer's data sheet, is 1.1 pF with a capacitance ratio of C (0 V)/C (10 V) = 7.5. The nonlinear capacitance (C_L) in each section is formed by two antiseries diodes. Shunt inductances (L_L) are implemented with a 0.6 mm wide suspended stripline connecting the pads to the ground plane. The length of these inductive lines is 5.7 mm. The pads on the board surface, together with an inherent parasitic effect (R_d), introduce unavoidable series inductance (L_R) and shunt capacitance (C_R), making the whole circuit a composite right/left-handed transmission line having an equivalent circuit shown in Figure 2(b).

Figure 3 compares the simulated and measured results of the fabricated LH NLTL. The simulation was performed with the CST Microwave Studio. Parameters of the equivalent circuit model in Figure 2(b) were extracted from the S-parameters simulated with the Ansys Designer circuit simulator: that is, $C_L = 1.1$ pF, $L_L = 1.8$ nH, $C_R = 0.4$ pF, $L_R = 0.7$ nH, and $R_d = 2.1$ Ohm. To enhance the bandwidth of the left-handed region and to minimize the parasitic effects, various simulations and experiments were conducted. Also, the number of LH NLTL sections was carefully selected through simulations to maximize device nonlinearity. The bandpass type frequency response with a Bragg cut-off frequency indicates the left-handed nature of the device. The LH high-pass cut-off frequency f_{cL} and the RH low-pass cut-off frequency f_{cR} can be calculated by using (1) and (2), respectively [13]:

$$f_{cL} = f_R \left| 1 - \sqrt{1 + \frac{f_L}{f_R}} \right|, \tag{1}$$

$$f_{cR} = f_R \left(1 + \sqrt{1 + \frac{f_L}{f_R}} \right), \tag{2}$$

where $f_R = 1/2\pi\sqrt{L_R C_R}$, $f_L = 1/2\pi\sqrt{L_L C_L}$.

In this paper, f_{cL} is chosen as 2 GHz and f_{cR} as 19 GHz. The measured frequency bandwidth of the fabricated LH NLTL agrees well with the calculated left-handed passband.

2.2. MS-to-SSL Transition Design. We designed the LH NLTL and a filter on suspended stripline because the suspended stripline offers a higher quality factor and wider impedance ranges as compared with other planar transmission lines [13]. To combine the advantages of suspended stripline and microstrip line simultaneously, a suitable and high performing transition structure between the two different transmission lines developed by the authors' group was utilized.

Figure 4 shows the picture of the ultrawideband MS-to-SSL transition fabricated in a back-to-back configuration.

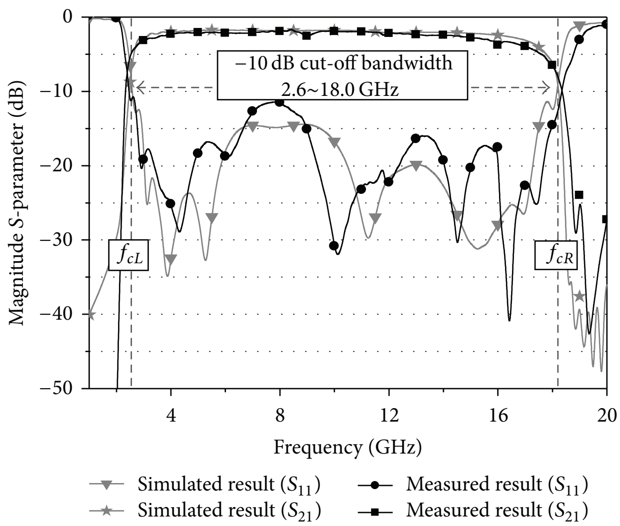


Figure 3: Simulated and measured results of the fabricated LH NLTL.

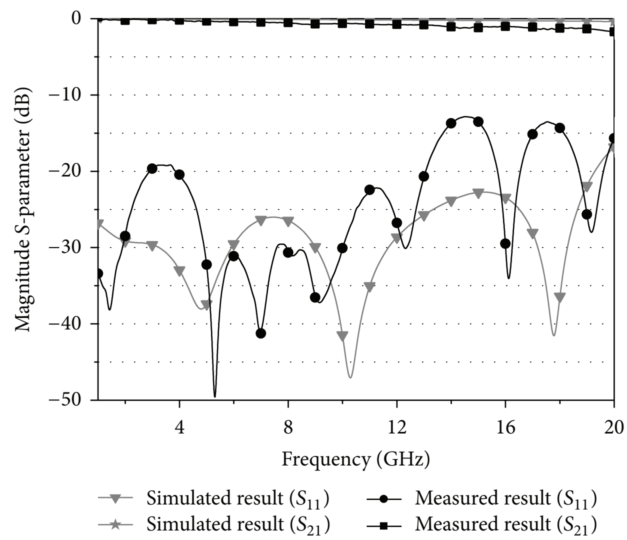


Figure 5: Simulated and measured results of the fabricated transition in a back-to-back configuration with connectors.

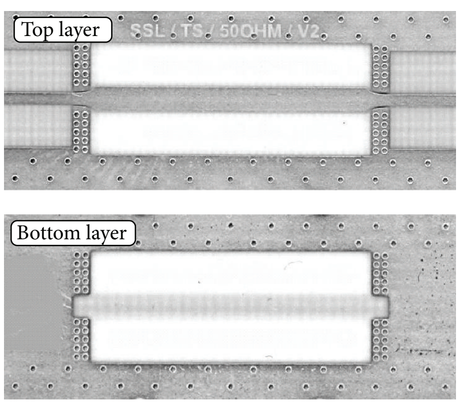


Figure 4: Fabricated microstrip-to-suspended stripline transition.

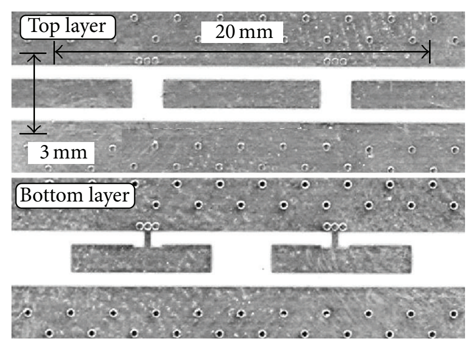


Figure 6: Picture of the fabricated high-pass filter.

The transition is designed to provide broadband impedance matching and smooth field transformation. Figure 5 compares the simulated and measured results of the transition. It is observed that the transition has less than 1.7 dB insertion loss and more than 10 dB return loss for frequencies from DC to 20 GHz. By subtracting the interconnection losses and the transmission line losses, the insertion loss of the implemented transition is estimated to be less than 0.5 dB per transition for frequencies up to 20 GHz.

2.3. High-Pass Filter Design. Figure 6 shows the picture of the fabricated suspended stripline 5th-order high-pass filter [14]. The fabricated high-pass filter is 20 mm by 3 mm in size, except for the connectors and extra space, and it has 5th-order Chebyshev response with a 0.5 dB in-band ripple. Figure 7 compares the simulated and measured results of the proposed filter. The passband is from 5.5 to 15 GHz (3 dB bandwidth). The minimum insertion loss is 0.2 dB. Parameters of the equivalent circuit model were simulated with the Ansys Designer circuit simulator: that is, $C_1 = 0.38$ pF, $C_2 = 0.22$ pF, and $L = 1.1$ nH.

2.4. Tripler Measurement. Figure 8 shows the picture of the proposed a suspended stripline frequency tripler using six-section LH NLTLs with a high-pass filter. The fabricated tripler is 30 mm by 7.5 mm in size, except for the connectors and extra space.

Figure 9 shows the conversion loss of the 3rd harmonic component and the suppression levels of the fundamental, 2nd, and 4th harmonics with +25 dBm of input power for the frequency range from 2.0 GHz to 3.1 GHz. The 3rd harmonic conversion loss ranges from 15.3 dB to 19.8 dB at +25 dBm of input power. The minimum 3rd harmonic conversion loss is 15.3 dB when the input frequency is 2.4 GHz. The fundamental frequency suppression level is typically over 50 dB, and 2nd and 4th harmonics frequency suppression levels are typically 30 dB. The decreased 2nd harmonic suppression over 2.5 GHz is obtained due to the action of the high-pass filter.

Table 1 compares the performance of the proposed tripler with those in other papers. It can be seen that the proposed LH NLTL-based tripler has wider frequency bandwidth and is smaller in size than other triplers reported in the literature.

Table 1: A performance comparison of frequency tripler.

Title	Structure	Frequency band [GHz]	Conversion Loss [dB]	Size [cm]
[9]	LPF + input matching + HBV + output matching + BPF	13.1~13.9 (*fo*) Pin = 22 dBm	11.2~17	2 × 1 Alumina
[10]	APDP (anti-parallel pair diode) + BPF	5.72~6.28 (*fo*) Pin = 22 dBm	16.6~18.5	5 × 2 RT5880
[11]	LPF + phase shifters + Schottky diode + BPF	7~9.5 (*fo*) Pin = 22 dBm	17~20	5 × 2 RO4003
This work	varactor diode + stub + HPF	2~3.1 (*fo*) Pin = 25 dBm	15.3~19.8	3 × 0.7 RO4003

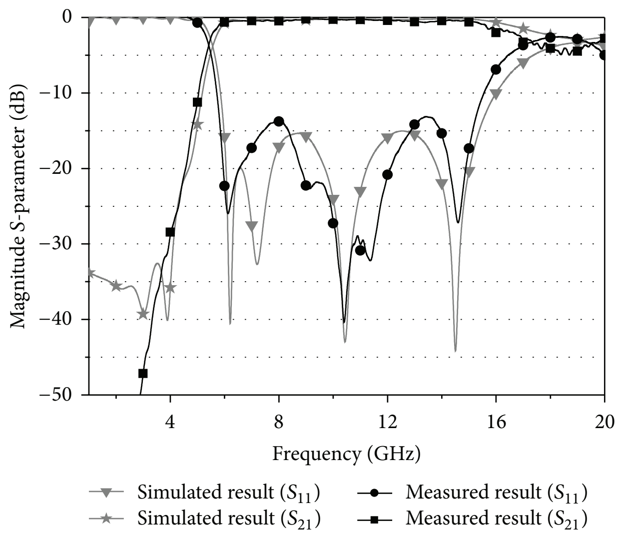


Figure 7: Simulated and measured results of the fabricated high-pass filter.

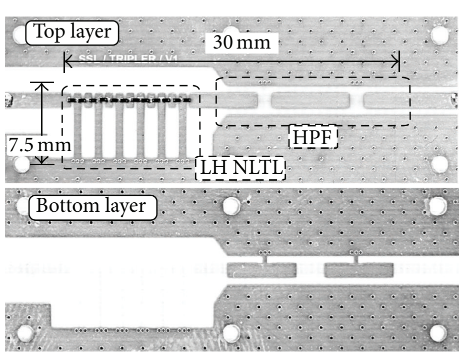


Figure 8: Picture of the fabricated tripler.

3. Conclusion

In this paper, we present a suspended stripline frequency tripler using a LH NLTL. The proposed tripler exhibits broader frequency bandwidth in a smaller size with comparable performance compared with the previously reported research results. The fabricated LH NLTL has a wide left-handed passband from 2.6 GHz to 18 GHz. The measured

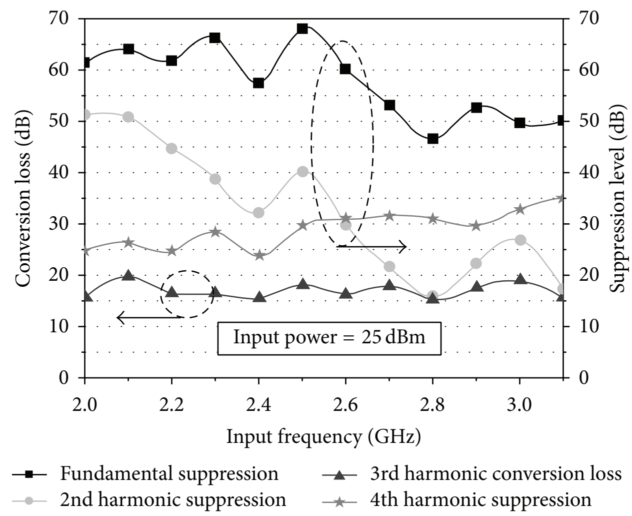


Figure 9: Third harmonic conversion loss and the suppression levels of the fundamental, 2nd, and 4th harmonics with +25 dBm of input power.

third harmonic conversion loss was typically 17 dB at an input frequency range from 2 GHz to 3.1 GHz. An ultrawideband microstrip-to-suspended stripline transition was used to easily integrate with microstrip-based circuits.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

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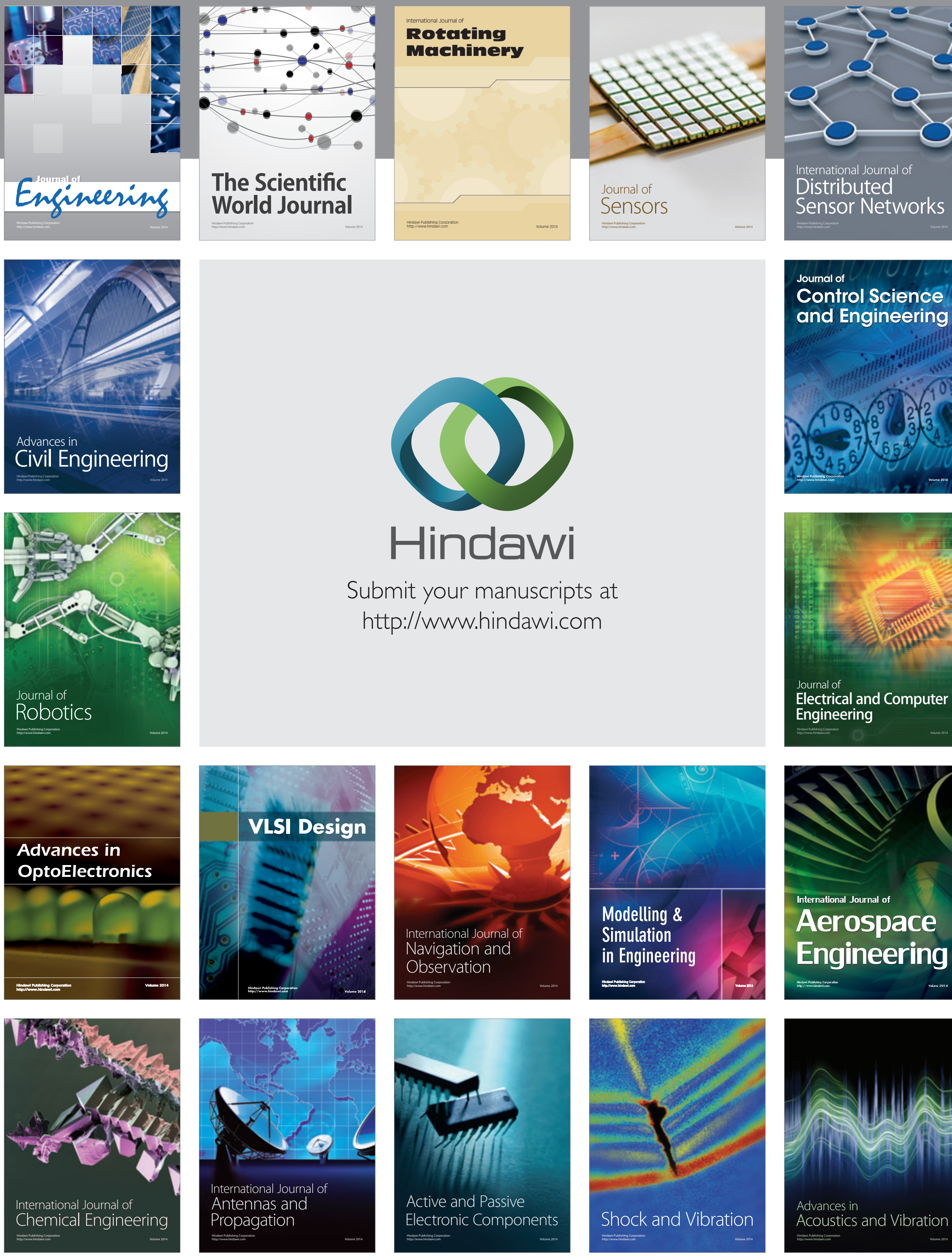
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