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Research Article

Temperature Sensor Using a Multiwavelength Erbium-Doped Fiber Ring Laser

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A novel temperature sensor is presented based on a multiwavelength erbium-doped fiber ring laser. The laser is comprised of fiber Bragg grating reflectors as the oscillation wavelength selecting filters. The performance of the temperature sensor in terms of both wavelength and laser output power was investigated, as well as the application of this system for remote temperature measurements.

1. Introduction

Multiwavelength erbium-doped fiber (EDF) lasers operating in the third communications window, with wavelengths around 1550 nm, are very attractive today because of their different applications in telecommunications, fiber sensors, and spectroscopy [1, 2]. Due to the homogeneous gain broadening of the EDF at room temperature, it is necessary to improve the inhomogeneity and suppress the mode hopping between the adjacent modes. Thus, many techniques have been proposed to obtain stable dual-wavelength oscillations, for example, by using highly nonlinear photonic crystal fibers [3], using saturable absorbers [4], or including a semiconductor optical amplifier in the ring cavity [5]. Fiber Bragg Gratings are suitable for use as spectrally narrowband reflectors for creating cavities for fiber lasers [6]. They represent one of the most exciting developments in the area of fiber optic communications and have also been used as strain or temperature sensors.

In this paper, we demonstrate a stable multiwavelength EDF laser at room temperature by incorporating three Fiber Bragg Gratings (FBGs) as the wavelength selecting filters. Experimental characterization has been performed, and a multiwavelength laser with oscillations at 1547 nm, 1550 nm, and 1555 nm has been achieved. Experimental results of the output power variation with temperature, as well as an output power and wavelength stability analysis with the temperature for the three FBGs, were carried out, showing the good performance of this laser as temperature sensor. Finally, the application of this system for remote temperature sensing was demonstrated.

2. Experimental Setup

2.1. Experimental Ring Laser Setup. The experimental setup of the proposed erbium-doped fiber laser is shown in Figure 1. A 980 nm pump source with 70 mW of pump power is used. This pump power is coupled to a 5 m highly erbium-doped fiber gain medium (EDF) (I-25 by Fibercore, with an absorption of 30 dB/m at 980 nm), by using a wavelength division multiplexer (WDM) coupler. The laser includes one ring cavity (as shown in Figure 1).

An optical loop mirror composed of single-mode optical fiber (SMF) with a 70 : 30 loop power-splitting ratio is inserted in the ring cavity to provide the intensity dependent loss for the lasing wavelengths, as proposed in [7].

A three-port circulator and three FBGs centered at 1547 nm, 1550 nm, and 1555 nm, with reflectivities of 98%, are used. The wavelength selection is carried out by means

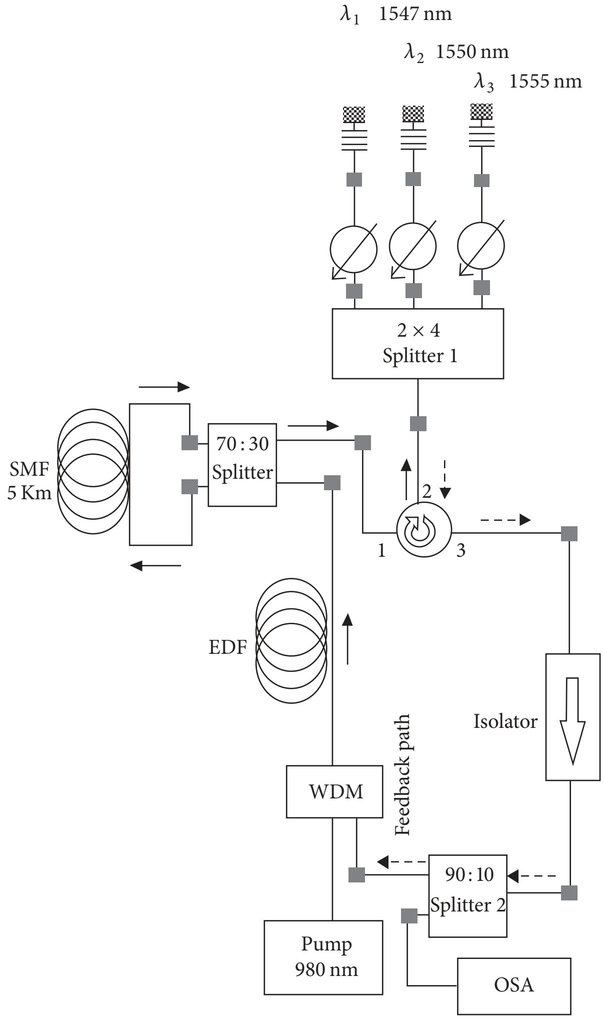


Figure 1: Experimental setup of an erbium-doped fiber ring laser (SMF: single-mode fiber; WDM: wavelength division multiplexer).

of the FBGs. This configuration was also composed of a 2 × 4 coupler to incorporate the three FBGs into the laser cavity and a 90 : 10 coupler to extract the laser output to be monitored by an Optical Spectrum Analyzer (OSA). In this setup, a circulator and an optical isolator were used inside the cavity to insert the FBGs' reflected signals and to ensure unidirectional operation, therefore avoiding the spatial hole-burning (SHB) effect. The experiment was run at room temperature and the length of the SMF was 5 km. Other lengths of SMF fiber, such as 2 km and 10 km, were also proven but the best results concerning optical power and stability were obtained with 5 km of SMF fiber.

Variable attenuators (VAs) have been connected to each FBG in order to correctly adjust the cavity losses on each wavelength to achieve oscillation of the system at the desired wavelengths.

Once we have the setup prepared, the next step is to study the behavior of the system as temperature sensor. For this purpose, the FBGs are used as sensing elements. Temperature changes translate into variations of the Bragg wavelength of the FBGs (λ_B). By monitoring this variation and the position of λ_B, the temperature is obtained, following an approximately linear relationship.

2.2. Experimental Remote Sensing System. To demonstrate the applicability of this system for remote sensing, a new fiber ring laser is proposed. This new setup incorporated two spools of 25 km of standard single-mode fiber after ports 1 and 3 of the circulator. This fiber spools simulate a 50 km long remote system. In this way, the light through the cavity is coupled into the ring. As in the previous case, the spectrum reflected from the sensors is amplified by a 5 m long EDF before it is directed to the ring. The output of the laser is monitored by an OSA, which is connected to the 10% port of a 90 : 10 coupler. The rest of the setup is the same as the one used in the previous case.

3. Experimental Results

3.1. Experimental Ring Laser Setup. The laser was pumped at 70 mW, and we used an OSA to monitor the output of the

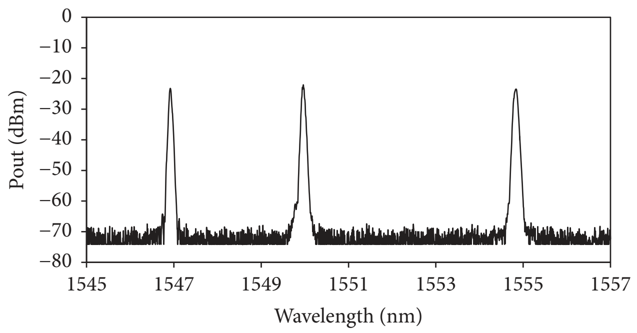


Figure 2: Spectrum of the multiwavelength laser.

Table 1: Average power and maximum power variation.

	1547 nm	1550 nm	1555 nm
Average power (dBm)	−24.41	−24.27	−24.60
Maximum power variation (dB)	2.01	2.26	3.71

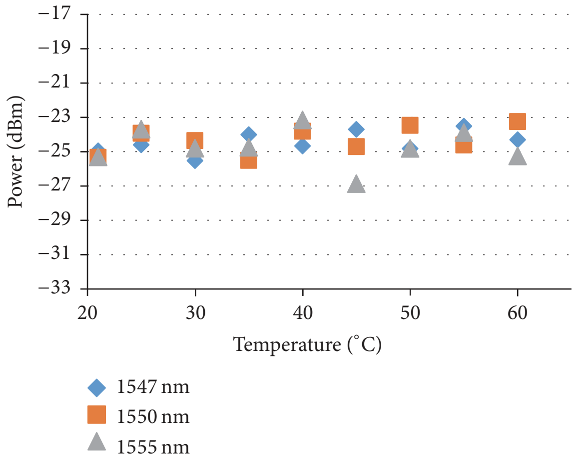


Figure 3: System's stability with temperature for the three sensors.

Table 2: R^2 values and sensors sensitivity for channels.

	1547 nm	1550 nm	1555 nm
R^2	0.9618	0.9848	0.9573
Sensitivity (pm/°C)	7.7	8.9	8.2

Table 3: Average power and maximum power variation.

	1547 nm	1550 nm	1555 nm
Average power (dBm)	−38.67	−38.86	−39.42
Maximum power variation (dB)	2.96	3.5	6.19

laser. In a series of experiments, the configuration in Figure 1 was used.

The average power from the signal wavelengths whose peak wavelengths are 1547 nm, 1550 nm, and 1555 nm, is higher than −25 dBm, as shown in Figure 2. As can be seen in Table 1, the maximum power variation for the three channels is about 3 dB.

As shown in Figure 2 and Table 1, power equalization for the three channels is obtained. The average power variation between the three sensors is below 1 dB and the average power is approximately −24 dBm. Concerning the maximum power variation, the values obtained are very low, so it is a very stable system.

Figure 3 shows the system's stability with temperature when the laser is lasing at the three wavelengths given by the FBGs.

Figure 4 shows the power and wavelength stability of this structure versus temperature variations. In this way, the three FBGs were placed inside a climatic chamber and temperature cycles from 25°C to 70°C with a 5°C step were performed.

Figure 4 represents the averaged wavelength increment for the three FBGs when the temperature is increased.

R^2 indicates the linearity of the graph. If it is near 1, it means it is more linear. In the three channels R^2 is higher than 0.95 (Table 2). This indicates very linear responses. Next step is to calculate the sensitivity of the FBGs with respect to the temperature. Thus, the temperature according to the wavelength displacement is estimated.

The linearity of the system response versus temperature is essential in order to achieve a reliable temperature sensor. As the dependence of the wavelength with respect to the temperature is more linear, we would obtain the temperature from the wavelength variation with greater accuracy and reliability.

As shown in Table 2, the averaged wavelength increment was approximately 7.7 pm/°C, 8.9 pm/°C, and 8.2 pm/°C for channels at 1547 nm, 1550 nm, and 1555 nm, respectively. The system's sensitivity is about 8 pm/°C. Thus, this analysis is in good accordance with previous works [8–10].

3.2. Experimental Remote Sensing System. The same measurements were carried out with the remote system.

The average power from the three signal wavelengths is around −39 dBm for the three channels, as shown in Figure 5. As can be seen in Table 3, the maximum power variation for the channels centered at 1547 nm and 1550 nm is about 5 dB. However, for the third channel at 1555 nm, the maximum variation is around 6 dB.

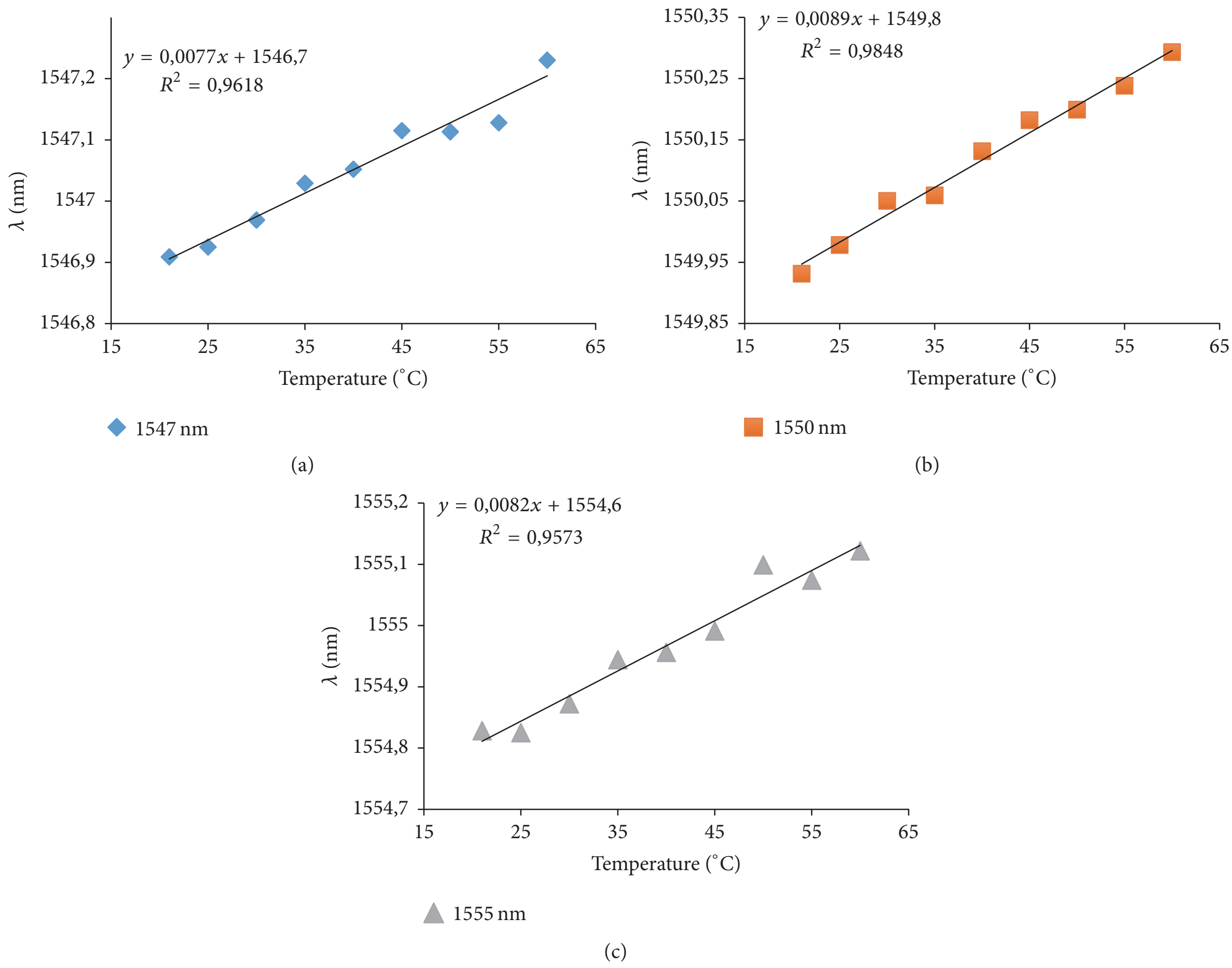
Figure 6 shows the system's stability with temperature when the laser is lasing at the three wavelengths given by the FBGs.

Figure 7 represents the sensitivity of the FBGs with respect to the temperature. In the three cases, the wavelengths increased with temperature.

As shown in Table 4, R^2 is around 0.9 in the three channels. This indicates very linear responses.

Table 4 represents the comparison between both sensing systems. The nonremote system presents slightly higher R^2 values. However, the values achieved with the remote system are close to 1 (total linearity), so that the λ-dependency with temperature could be considered linear. This means that the system could be used as a temperature sensor.

Once the linearity of the remote sensor is verified, its sensibility or its λ-variation with temperature is checked. The results are as expected, near 8 pm/°C [8–10]. If we compared



(a)

(b)

(c)

Figure 4: (a) Wavelength variation with temperature for the sensor centered at 1547 nm, (b) for the sensor centered at 1550 nm, and (c) for the sensor centered at 1555 nm.

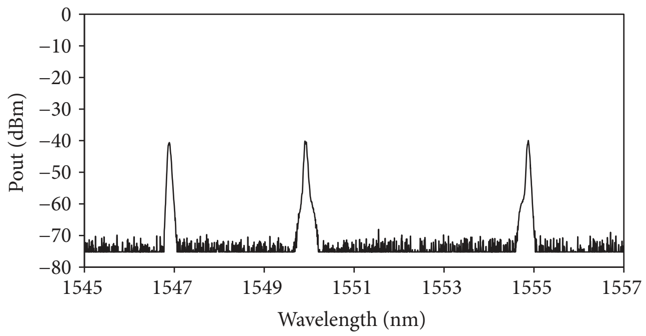


Figure 5: Spectrum of the remote multiwavelength laser.

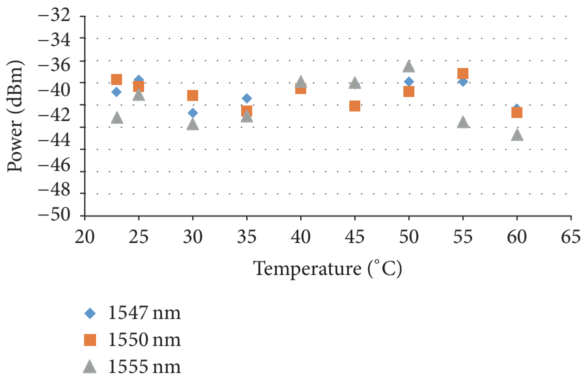


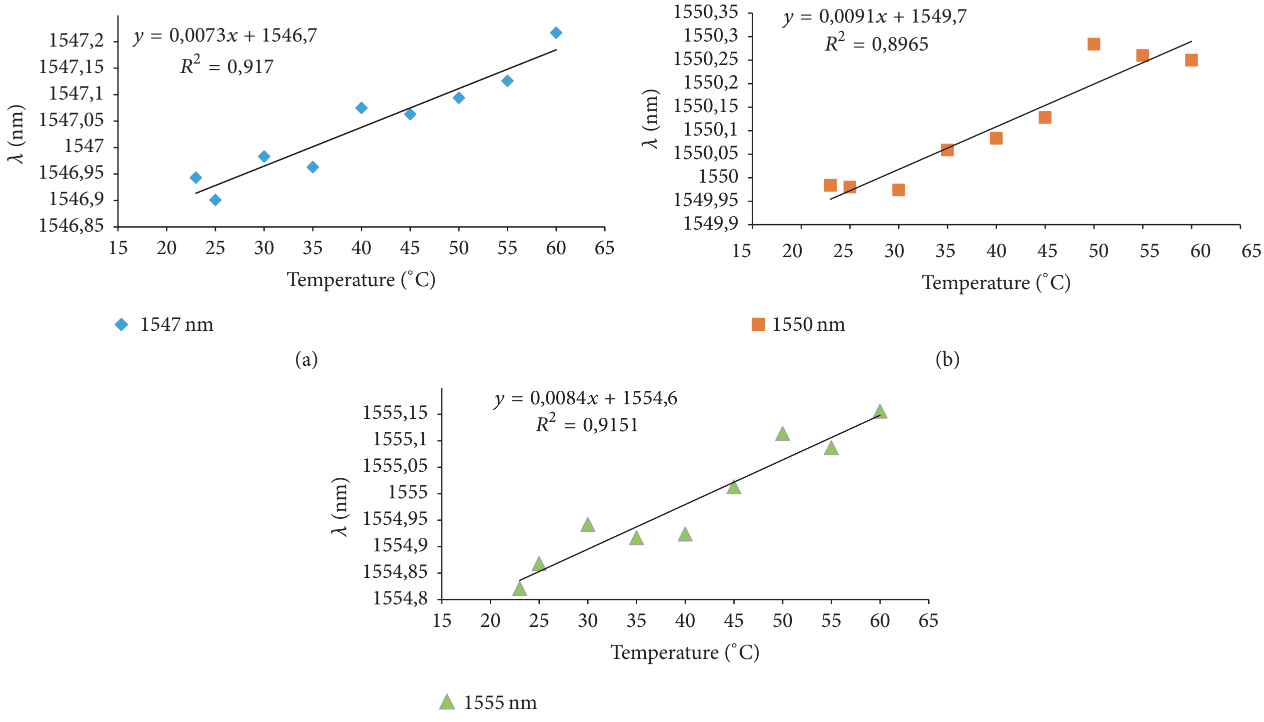
Figure 6: Stability for the remote system with temperature.

the results for both sensing systems, they are quite similar (see Table 5). The channel centered at 1547 nm is less sensitive than the rest, but the other two channels are slightly more sensitive to temperature changes.

Nevertheless, these differences are very low, 0.4 pm/°C in the worst case (for the sensor centered at 1547 nm), so that they could be neglected.

4. Conclusions

A novel configuration of a temperature sensor has been obtained by using a stable multiwavelength erbium-doped fiber ring laser. The laser employs three FBGs to select the operation wavelengths and as sensing elements.



(a)

(b)

(c)

Figure 7: (a) Wavelength variation with temperature for the remote sensor centered at 1547 nm, (b) for the remote sensor centered at 1550 nm, and (c) for the remote sensor centered at 1555 nm.

Table 4: R^2 values for both sensing systems.

	1547 nm	1550 nm	1555 nm
R^2 for nonremote system	0.9618	0.9848	0.9573
R^2 for remote system	0.9170	0.8965	0.9151

Table 5: Sensitivity for both sensing systems.

	1547 nm	1550 nm	1555 nm
Sensitivity for nonremote system (pm/°C)	7.7	8.9	8.2
Sensitivity for remote system (pm/°C)	7.3	9.1	8.4

Temperature measurements have been carried out with the structure and good linearity and stability results have been shown. As for the linearity of the sensors, the wavelength variation with respect to temperature changes is very linear. In the three channels, R^2 is between 0.9573 and 0.9848. Regarding sensitivity, the more sensitive channel is the one centered at 1550 nm with 8.9 pm/°C and the least sensitive one is the one located at 1547 nm with 7.7 pm/°C. These two results are near enough to be considered independent of the channel sensor response. From these results, it can be said that the system is optimal as temperature sensor and this structure offers promising results for the design of sensors applications in the future.

Finally, the application of this system for remote temperature measurements has been demonstrated. It shows values of R^2 higher than 0.89 in the three cases, so that it could be considered a linear system. The sensitivity was between 7.3 and 9.1 pm/°C for the three channels, over the temperature range from 25 to 70°C when the sensing distance is about 50 km.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] A. Bellemare, "Continuous-wave silica-based erbium-doped fibre lasers," *Progress in Quantum Electronics*, vol. 27, no. 4, pp. 211–266, 2003.

[2] J. M. Lopez-Higuera, "HandBook of Optical Fibre Sensing Technology (Wiley, 2002)".

[3] J. Canning, N. Groothoff, E. Buckley, T. Ryan, K. Lyytikainen, and J. Digweed, "All-fibre photonic crystal distributed Bragg reflector (PC-DBR) fibre laser," *Optics Express*, vol. 11, no. 17, pp. 1995–2000, 2003.

[4] S. Feng, O. Xu, S. Lu, T. Ning, and S. Jian, "Switchable single-longitudinal-mode dual-wavelength erbium-doped fiber ring laser based on one polarization-maintaining fiber Bragg grating incorporating saturable absorber and feedback fiber loop," *Optics Communications*, vol. 282, no. 11, pp. 2165–2168, 2009.

[5] S. Pan, Z. Xiaofan, and L. Caiyun, "Switchable single-longitudinal-mode dual-wavelength erbium-doped fiber ring laser incorporating a semiconductor optical amplifier," *Optics Letters*, vol. 33, no. 8, pp. 764–766, 2008.

[6] C. H. Yeh, C. W. Chow, J. Y. Chen, H. Z. Chen, J. H. Chen, and W. F. Liu, "Utilizing simple FBG-based erbium-doped fiber architecture for remote temperature sensing," *Laser Physics*, vol. 25, no. 10, Article ID 105102, 2015.

[7] S. Qhumayo, R. M. Manuel, and M. Grobler, "Wavelength and power stabilization of a three wavelength Erbium doped fiber laser using a nonlinear optical loop mirror," in *Proceedings of the 12th IEEE AFRICON International Conference (AFRICON '15)*, pp. 1–4, September 2015.

[8] S. Diaz, "Stable dual-wavelength erbium fiber ring laser with optical feedback for remote sensing," *Journal of Lightwave Technology*, vol. 34, no. 19, Article ID 7433373, pp. 4591–4595, 2016.

[9] S. Diaz, A. B. Socorro, R. M. Manuel, R. Fernandez, and I. Monasterio, "Stable multi-wavelength fiber lasers for temperature measurements using an optical loop mirror," *Applied Optics*, vol. 55, no. 29, pp. 8385–8389, 2016.

[10] S. Diaz and M. Lopez-Amo, in *Proceedings of the SPIE*, vol. 9634, pp. 9634761–9634764, 2015.


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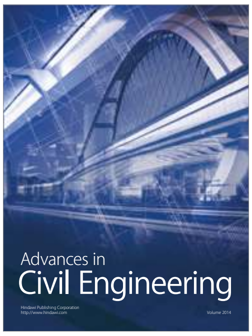
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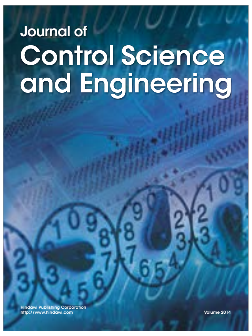
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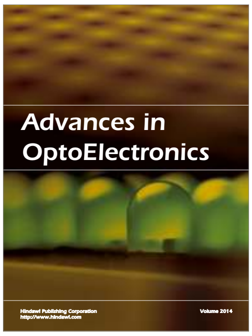
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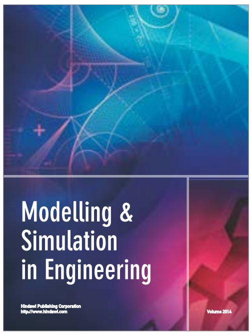
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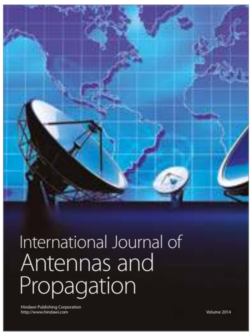
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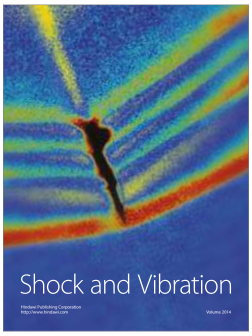
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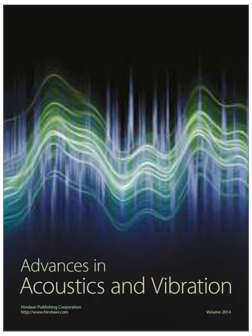
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