Metamaterial split ring resonator as a sensitive mechanical vibration sensor

Sikha Simon K., Sreedevi P. Chakyar, Jolly Andrews, and Joseph V. P.

Citation: AIP Conference Proceedings **1849**, 020021 (2017); doi: 10.1063/1.4984168
View online: http://dx.doi.org/10.1063/1.4984168
View Table of Contents: http://aip.scitation.org/toc/apc/1849/1
Published by the American Institute of Physics

Metamaterial Split Ring Resonator as a Sensitive Mechanical Vibration Sensor

Sikha Simon K.[1], Sreedevi P. Chakyar[1], Jolly Andrews[1] and Joseph V.P.[1, a)]

[1] *Department of Physics, Christ College (Autonomous), Irinjalakuda, University of Calicut, Kerala, India.*

[a)] Corresponding author: drvpjo@gmail.com

Abstract. This paper introduces a sensitive vibration sensor based on microwave metamaterial Split Ring Resonator (SRR) capable of detecting any ground vibration. The experimental setup consists of single Broad-side Coupled SRR (BCSRR) unit fixed on a cantilever capable of sensitive vibrations. It is arranged between transmitting and receiving probes of a microwave measurement system. The absorption level variations at the resonant frequency due to the displacement from the reference plane of SRR, which is a function of the strength of external mechanical vibration, is analyzed. This portable and cost effective sensor working on a single frequency is observed to be capable of detecting even very weak vibrations. This may find potential applications in the field of tamper-proofing, mining, quarrying and earthquake sensing.

INTRODUCTION

The significant advancements in different scientific fields and subsequent innovations in various technological realm have made human life more comfortable and secure. It is now an almost accepted fact that this speedy and rigorous developments have brought, along with its manifold comforts, serious negligence in various safety measures. Apart from naturally occurring earthquakes and landslides, unscientific and unethical ground water excavations and mining may trigger major vibrations on different layers of earth. The impacts of heavy machineries used in construction fields for tunneling, piling, quarrying and the hectic transportations of heavy trains and trucks are some other sources which trigger ground vibrations. Another serious concern is in the area of multi-storey building constructions without properly considering the possible effects of ground vibrations due to various natural and man-made sources. Many of the aged buildings which are still in use, and have not met modern safety measures, are more prone to vibrations which may even lead to collapse.

Different types of seismometers are used to detect the earthquake related ground vibrations. Though the seismic sensing technology is well developed, other possibilities for detecting ground vibrations are rarely seen in literature. Some of other vibration sensors proposed, make use of piezoelectric, photoelectric, optoelectronic, magneto inductive and capacitive properties [1-4]. Recently, the emerging field of metamaterials proposes different types of sensitive sensors that could find potential applications in bio-sensing, strain sensing, pressure sensing, temperature sensing etc. [5-9].

Metamaterials are a new class of artificially engineered materials having unusual properties due to negative permittivity ε, negative permeability μ and negative refractive index n [10-13]. Physics of these materials are totally different from other materials which are having positive refractive index. Split Ring Resonator (SRR), which consists of two concentric metallic rings having splits in diametrically opposite sides, is a basic building block of negative permeability medium [14-17]. Different variants of SRR structures reported are Edge Coupled SRR (conventional SRR-ECSRR), Broad-side Coupled SRR (BCSRR), Double sided SRR (DSRR) etc. [18-21]. In this paper, by making use of capacitive property of BCSRR, we are introducing a new vibration sensor for sensing all

Let There be Light
AIP Conf. Proc. 1849, 020021-1–020021-8; doi: 10.1063/1.4984168
Published by AIP Publishing. 978-0-7354-1521-8/$30.00

types of sensitive earth vibrations. This may find potential applications in addressing the security concerns related to vibrations caused by natural and human sources.

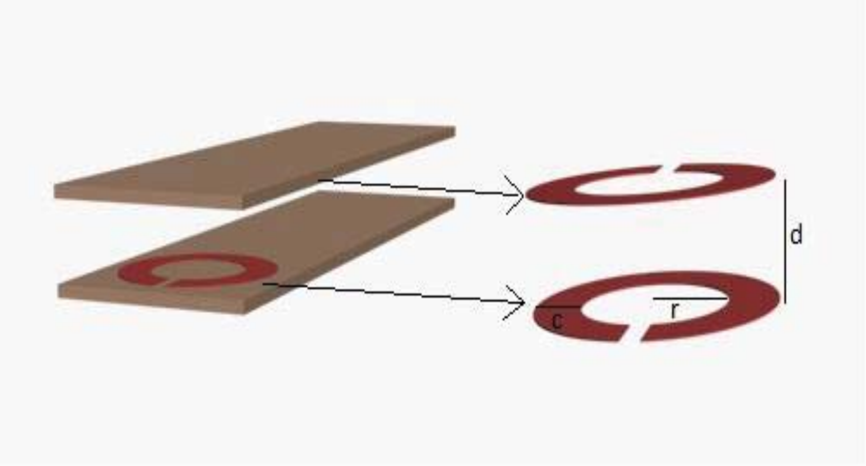

FIGURE 1. Schematic representation of BCSRR with structural parameters

DESIGN AND THEORETICAL CONCEPT

Conventional BCSRR consists of two metallic rings of same dimensions with small splits in opposite ends, etched on two sides of dielectric substrate usually on a double sided FR4 circuit board. The resonance frequency *f* of BCSRR depends on inductance *L* of the rings and capacitance *C* between the rings, given by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Capacitance *C* is a function of dielectric constant and thickness of substrate material, which are constant for a conventional BCSRR leading to a single resonance frequency value for fixed ring dimensions. In our case this limitation is overcome by fabricating two rings of the BCSRR separately on two substrate pieces of the same material and are arranged one over the other axially with air as dielectric, capable of varying the spacing *d* between them. This gives flexibility of changing the resonance frequency with high sensitivity. Figure 1 shows schematic representation of BCSRR with the structural parameters - radius *r*, width of the ring *c* and spacing between the rings *d*.

EXPERIMENTAL SETUP

The two rings of BCSRR are separately fabricated on two identical pieces of FR4 glass-epoxy board of permittivity $\varepsilon_r = 4.4$, thickness $t = 0.8$ mm, ring radius $r = 2$ mm and width of the ring $c = 1$ mm. In order to sense the ground vibrations and link them to the BCSRR, we have chosen a steel bar mounted on a wooden platform as a cantilever of length 25 cm, breadth 1 cm and thickness 0.75 mm. One of the BCSRR ring is fixed on the free end of the cantilever and the other ring is attached to a heavy base capable of micrometer movement in X-Y direction. By properly adjusting the micrometer screw, BCSRR ring is axially arranged over the other ring fixed on cantilever, symmetrically with splits in opposite direction as shown in Fig. 2. Two electrical probes connected to Vector

Network Analyzer (VNA), one acting as transmitter and other as receiver are arranged parallel to the plane of BCSRR as shown. The spacing *d* between the rings is adjusted to around 0.5 mm.


(a)
(b)

FIGURE 2. a) Photograph of a vibration sensor setup with cantilever and BCSRR system arranged between transmitting and receiving probes. b) Magnified view of BCSRR sensor probe.

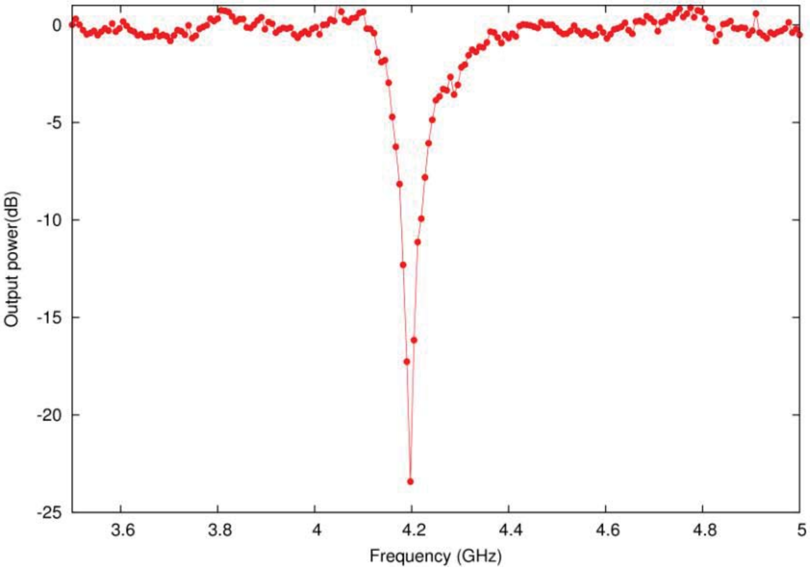

FIGURE 3. Transmission spectra of BCSRR sensor probe.

The transmission spectra of BCSRR sensor probe is shown in Fig. 3. The resonant absorption take place at 4.2 GHz. As spacing between rings increases its effective capacitance reduces which in turn increases resonant frequency considerably. We observed a shift in resonant frequency of around 3 GHz for 1 mm spacing. Thus resonance tunability observed for our BCSRR is 3 x $10^{-7}\mu$m/Hz. Due to the sensitiveness even small vibrations of the cantilever triggered by ground vibrations changes the spacing between rings and will result in changes in the corresponding shifts in resonance frequency. If we are selecting any fixed frequency near resonance absorption dip as operating frequency, even slight changes in capacitances due to very small vibrations, result in corresponding drastic changes in power level at the receiving port.

MEASUREMENTS AND RESULTS

We can choose operating frequency either on the rising or falling edges of the absorption curve. In the present experiment, we have selected operating frequency on the falling edge of the absorption curve. We have conducted the following experimental procedures in order to prove that our sensor setup can catch ground vibrations effectively.

Building Vibrations due to Human Activities

Human activities like walking, jumping, jogging etc. cause vibrations to the building which may often go unnoticed. These vibrations may be of different magnitudes depending upon the factors like structure and area of the room, storey number, weight of furniture and number of people inside the room and age of the building. To quantify these effects, we have conducted experiments in the following manner.

We have selected three platforms and performed walking, jogging and periodic jumping of small amplitude. The venue selected are two rooms on the first floor having different areas of concrete slab floor of 6 inch thickness and ceramic tile finishing and one in the ground floor with the same tile finishing. The rooms selected are of a four storey building of around 40,000 Sq ft constructed 60 years back. The area of first room on first floor is of 225 Sq ft without any furniture inside. Second room on the first floor is of 600 Sq ft area with around 500 Kg s furniture weight. The third room is on the ground floor having the same dimensions as that of the first room.

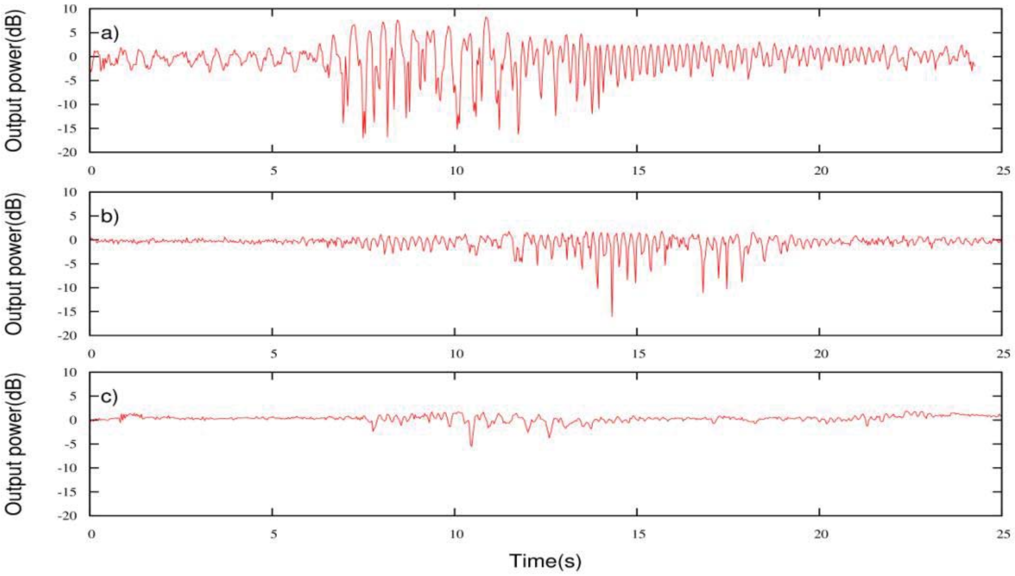

FIGURE 4. Output vibration pattern of sensor obtained by jogging in three experimental rooms. (a) Room - 1 in first floor with area 225 Sq ft, (b)Room - 2 in first floor with area 600 Sq ft. (c) Room - 3 in ground floor with 225 Sq ft.

As the first experiment we perform the effect of jogging in the above mentioned three rooms. Figure 4 shows the vibrations sensed by our sensor for a time period of 25 s. Figure 4 (a) depicts vibrations obtained when a person of 68 Kg jogged nearby the experimental setup. From the Fig. 4, it is clear that amplitude of the vibrations increases as the person approaches vibration sensor and persist for a small time even after the person moves away from the apparatus. Vibrations sensed by the sensor for the similar movement in room-2 and room-3 are shown in Fig. 4 (b) and Fig. 4 (c). Even though the area of the second room is much greater than that of the first room, due to presence of furniture which act as a shock absorber, reduces the amplitude of vibration significantly as it is evident in Fig. 4 (b). Since the third room is in ground floor, the vibrations triggered comparably less as is expected.

As the second experiment we performed periodic jumping with an amplitude of one feet for three times in the above mentioned three rooms by the same person. The results are given in Fig. 5. The Vibrational effects received by the sensor in similar manner as that of jogging, which is evident from the Fig. 5.

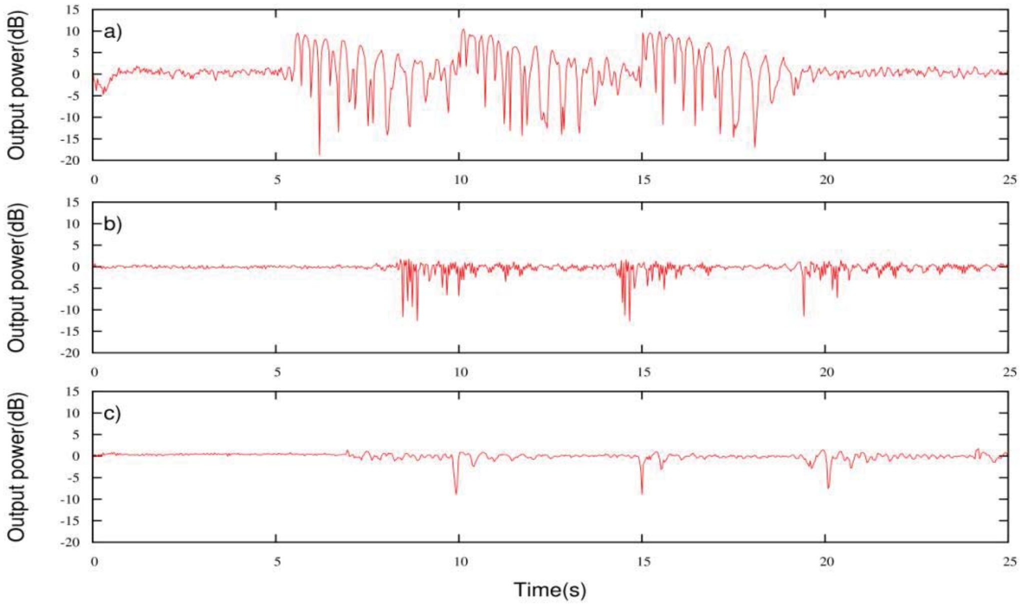

FIGURE 5. Output vibration pattern of sensor obtained by jumping in three experimental rooms. (a) Room - 1 in first floor with area 225 Sq ft, (b)Room - 2 in first floor with area 600 Sq ft, (c) Room - 3 in ground floor with 225 Sq ft.

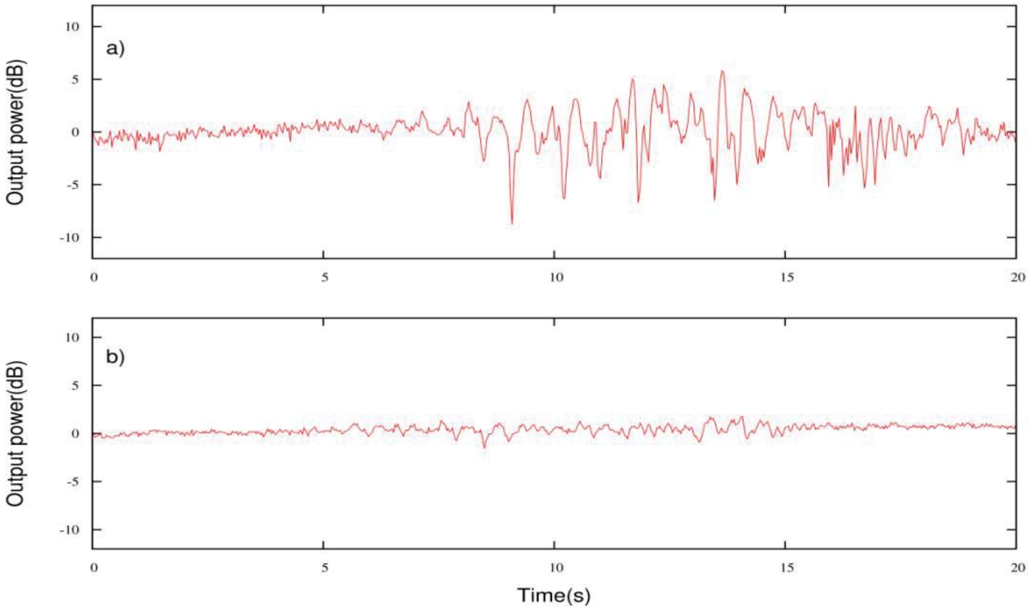

FIGURE 6. Output vibration pattern of sensor obtained by the sensor tuned to catch (a) high sensitive vibrations, (b) low sensitive vibrations.

Due to nonlinear nature of the rising and falling regions of the absorption curve, the sensitivity can be tuned by properly selecting operating frequency near to resonant point. As we move away from the resonance dip, sensitivity of the sensor also decreases and such cases will be suitable for detecting vibrations of large amplitude. In order to check the sensitivity of our probe, we have carried out a walking experiment in room-3 which is in ground floor where vibration is comparatively less. Walking is performed by the same person who moved nearby the vibration sensor and the resulting vibrations are plotted in Fig. 6. Figure 6 (a) shows the vibrations when the operating frequency is selected near resonance point for catching sensitive vibrations where as Fig. 6 (b) is for less sensitive operating frequency. It is observed that even tip-toeing can be detected by properly tuning out the sensitivity of our vibration sensor.

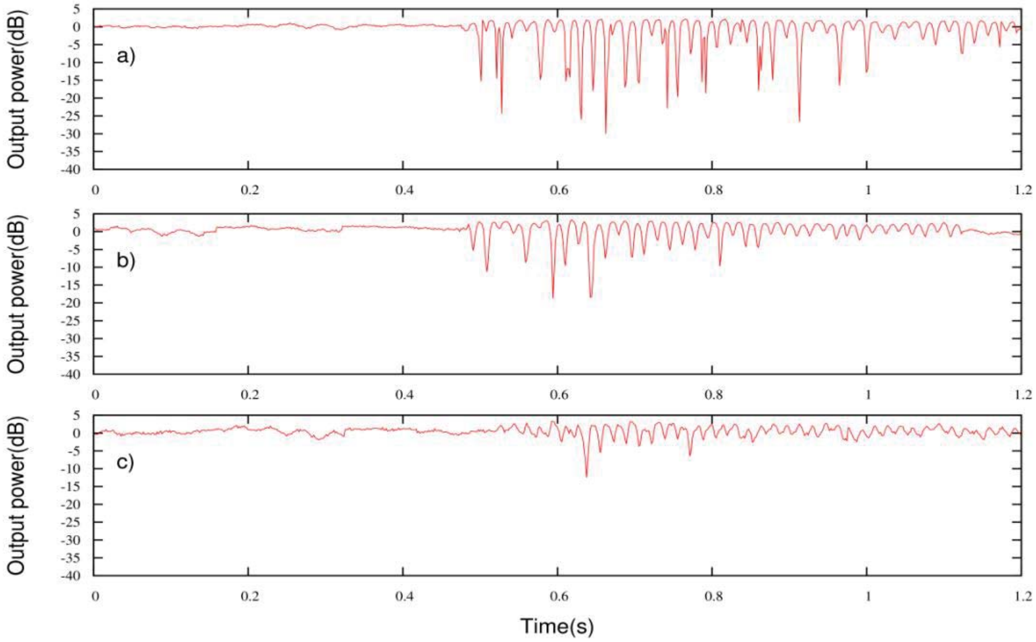

FIGURE 7. Output vibration pattern due to freely falling three standard weights from a height of 20 cm at a fixed distance 150 cm from the vibration sensor - (a) 100 gm, (b) 50 gm, (c) 20 gm.

Imparted Vibrations due to Freely Falling Standard Weights

In order to further check the sensitivity of our vibration sensor, we have performed another set of experiments by using freely falling standard weights. The sensor setup is arranged on a wooden table of area 20 Sq ft. Standard weights of 100 gm, 50gm and 20 gm are allowed to fall freely on the experimental desk from various heights at different distances from the vibration sensor. The corresponding vibrations sensed by the sensor are analyzed.

As the first experiment, standard weights of 100 gm, 50 gm and 20 gm are allowed to fall freely on the experimental table from a fixed height of 20 cm at a distance of 150 cm from the apparatus. The results are shown in Fig. 7. Figure 7 (a) shows the output vibration pattern obtained for the weight of 100 gm. The amplitude of vibrations decreases progressively for weights 50 gm and 20 gm as it is evident from Fig. 7 (b) and Fig. 7 (c).

As a second step a standard weight of 100 gm from three heights 10 cm, 20 cm and 30 cm at a fixed distance of 150 cm from our sensor, is allowed to fall freely on the experimental table. The output vibration pattern corresponding to three heights 10 cm, 20 cm and 30 cm is shown in Fig. 8. The amplitude of vibrations is very high for the height 30 cm as compared to other two heights which is depicted in Fig. 8 (c). As the height decreases the amplitude of vibrations decreases progressively as expected.

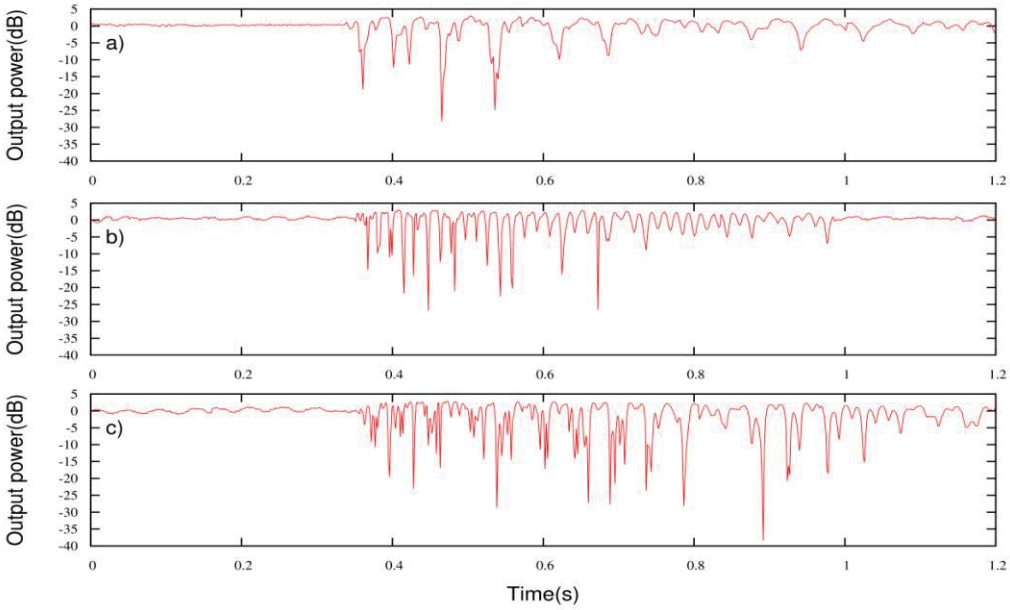

FIGURE 8. Output vibration pattern due to freely falling a standard weight of 100 gm from three heights at a distance of 150 cm from the vibration sensor - (a) 10 cm, (b) 20 cm, (c) 30 cm.

Measurements are repeated for a standard weight of 100 gm from a fixed height of 20 cm for three distances 50 cm, 100 cm and 150 cm from the vibration sensor and observed vibration pattern is shown in Fig. 9. This also verifies that the sensor can catch the strength of vibrations of higher and lower magnitude.

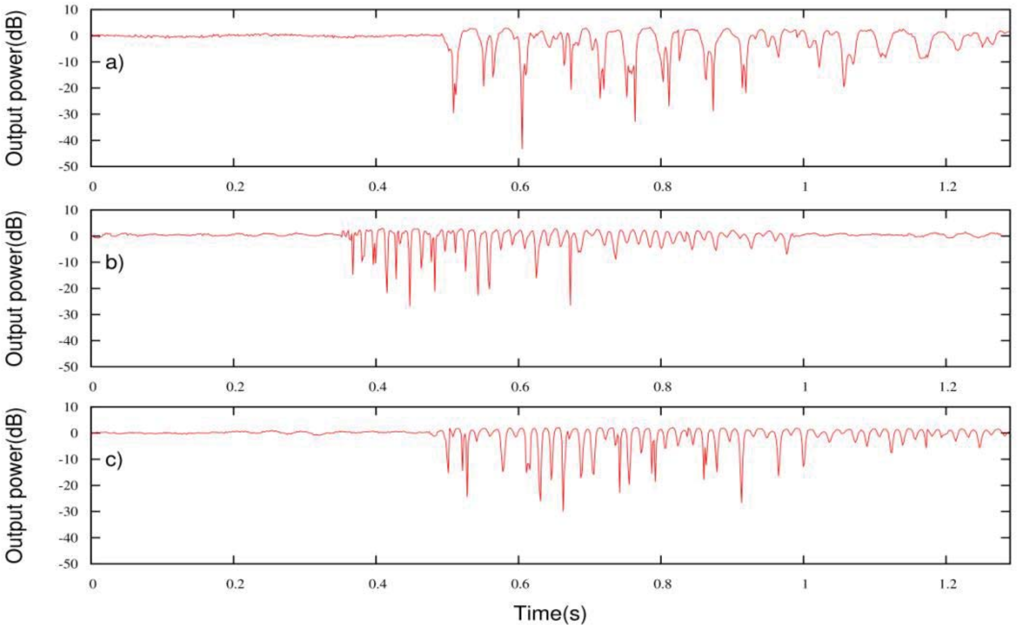

FIGURE 9. Output vibration pattern due to freely falling a standard weight of 100 gm from a height of 20 cm kept at three distances from the vibration sensor - (a) 50 cm, (b) 100 cm, (c) 150 cm.

CONCLUSION

We have introduced metamaterial SRR based sensitive vibration sensor capable of detecting any type of ground vibrations. An experimental setup consists of a BCSRR based vibration sensor, arranged between microwave transmitter and receiver. The sensitivity of our vibration sensor may be tuned by selecting the operating frequency very near to the resonance frequency of SRR resonator for sensing even very weak vibrations. This novel sensor may find potential applications in detecting any mechanical ground vibrations produced by all natural and man-made origin. Since the sensor works on a single frequency, it can be easily realized using a gun diode setup which will quite cheap and have the added advantage of portability as required in many field works.

REFERENCES

1. Z. Xiao-yan, J. Shandong Inst. Commerce Tech. **7**, 102–106 (2007).
2. Y. Cao, X. L. Rong, S. J. Shao, and K. P. He, “ Present situation and prospects of vibration sensors, ” in *Computer Distributed Control and Intelligent Environmental Monitoring (CDCIEM), 2012* International Conference on (IEEE, 2012), pp. 515–518.
3. X. Fu-cheng, Practical Electronics **10**, 13–15 (2008).
4. S. SUN, J. Elec. Meas. Instrum. **23**, 1–10 (2009).
5. R. Melik, E. Unal, N. K. Perkgoz, C. Puttlitz, and H. V. Demir, Opt. Exp. **18**, 5000–5007 (2010).
6. S. Raghavan and V. Rajeshkumar, Session 2A8 **245**, 25–28 (2013).
7. H. Karim, D. Delfin, M. A. I. Shuvo, L. A. Chavez, C. R. Garcia, J. H. Barton, S. M. Gaytan, M. A. Cadena, R. C. Rumpf, R. B. Wicker, et al., IEEE Sensors J. **15**, 1445–1452 (2015).
8. R. Melik, E. Unal, N. K. Perkgoz, C. Puttlitz, and H. V. Demir, Appl. Phys. Letters **95**, p. 181105 (2009).
9. S. P. Chakyar, J. Andrews, and V. P. Joseph, World Academy of Science, Engineering and Technology, Int. J. Mech., Aero., Ind., Mechat. and Manuf. Eng. **10**, 1030–1033.
10. D. R. Smith, J. B. Pendry, and M. C. Wiltshire, Science **305**, 788–792 (2004).
11. J. B. Pendry, Phys. Rev. Letters **85**, 3966–3969Oct (2000).
12. V. G. Veselago, Sov. Phys. Usp. **10**, p. 509 (1968).
13. D. R. Smith, W. J. Padilla, D. Vier, S. C. Nemat-Nasser, and S. Schultz, Phys. Rev. Lett. **84**, p. 4184 (2000).
14. B. Lahiri, “Split ring resonator (srr) based metamaterials,” Ph.D. thesis, University of Glasgow 2010.
15. K. Aydin, I. Bulu, K. Guven, M. Kafesaki, C. M. Soukoulis, and E. Ozbay, New J. Phys. **7**, p. 168, (2005).
16. Z. Sheng and V. V. Varadan, J. App. Phys. **101**, p. 014909 (2007).
17. P. M. Ragi, K. Umadevi, P. Nees, J. Jose, M. Keerthy, and V. P. Joseph, Microw. Opt. Tech. Lett. **54**, 1415–1416 (2012).
18. Z. Jakˇsi´c, O. Jakˇsi´c, Z. Djuri´c, and C. Kment, J. Opt. A: Pure App. Opt. **9**, p. S377 (2007).
19. H.-J. Lee, H.-S. Lee, K.-H. Yoo, and J.-G. Yook, J. App. Phys. **108**, p. 014908 (2010).
20. E. Ekmekci and G. Turhan-Sayan, App. Phys. A **110**, 189–197 (2013).
21. E. Ekmekci and G. Turhan-Sayan, PIER B **12**, 35–62 (2009).