Progress In Electromagnetics Research B, Vol. 38, 57–70, 2012

RECONFIGURABLE FISHNET METAMATERIAL USING PNEUMATIC ACTUATION

I. E. Khodasevych*, W. S. T. Rowe, and A. Mitchell

Electrical and Computer Engineering, RMIT University, Melbourne, VIC 3001, Australia

Abstract—The design, fabrication and measurement of a reconfigurable fishnet metamaterial based on a new method of tuning by changing unit cell geometry is reported. Retractable elements are added to the unit cell utilizing pneumatically actuated switching. It is shown that the pneumatic actuation approach can unite a number of metallic elements into a complex conducting structure. Experimental demonstration confirms that the structure operates at two different frequencies in the GHz range in distinct actuation states. The measured results also show good agreement with numerical simulations.

1. INTRODUCTION

It has been suggested long ago that artificially created composite materials could exhibit properties not found in natural materials, like simultaneously negative permittivity and permeability and negative refraction [1]. Since the first metamaterial was demonstrated for microwave frequencies [2], a number of different designs have been proposed to improve performance and enable the metamaterials to operate at higher frequencies. The fishnet metamaterial consists of patterned metal layers separated by dielectric spacer [3]. It is capable of operating up to the optical frequency range [4], is easy to fabricate due to its planar structure, and can exhibit negative refractive index under normal illumination by incident wave.

As the principle of metamaterial operation is based on the resonant response of the constituting elements, it exhibits unusual properties in a very narrow frequency band. Thus, for many of the proposed applications, it will be desirable to reconfigure the properties of the metamaterial to shift the frequency at which this resonance occurs.

Received 25 October 2011, Accepted 4 January 2012, Scheduled 11 January 2012
* Corresponding author: Iryna Khodasevych (iryna.khodasevych@student.rmit.edu.au).

One of the approaches to the tunability of metamaterials has involved the variation of substrate properties. A vanadium dioxide substrate was used in [5] to trigger an insulator to metal transition by heating the material, and the conductivity of a semiconducting substrate was altered by laser irradiation in [6]. These techniques require substantial modification of the material surroundings or the use of additional complex equipment. The extent to which dielectric properties of the substrate can be varied also limits the range in which the structure can be tuned. The change of substrate state was temporary and the structure reverted to its original condition.

Alternatively, previous theoretical investigations have shown that changing the geometry of the metallic elements resulted in more substantial shift in the resonant frequency of the structure [7, 8]. The challenge of this approach is the permanent nature of metallic patterns on the substrate after fabrication is completed. One of the latest achievements in this direction involved using MEMS switches to close gaps in split-ring resonators [9, 10].

It is hypothesized the more substantial variations in geometry of a metamaterial unit cell can be achieved by adding extra metallic elements where desired to an already existing structure through pneumatic actuation. By ensuring good electric contact, the separate elements can be united into a more complex conducting structure. The significant advantage of pneumatic switching as compared to MEMS switches is that metallic elements of arbitrary shapes and numbers can be combined using the same or different actuating membranes. This can result in a wider range of tuning effects on the structure, not limited to simply acting as a switch or filter. Pneumatic switching can occupy less space than MEMS switches since pneumatic chamber walls and membranes can be made fractions of a micrometer thick [11, 12]. Hence the switching elements can be made smaller and closer together to achieve greater tuning flexibility. Pneumatic switches can also maintain their state for some time when disconnected from the vacuum source, unlike devices requiring constant power supply. However, the major advantage of pneumatic actuation is the elimination of metallic biasing wires in the structure which can interfere with the metamaterial operation and may be prone to damage in a harsh environment.

Pneumatic micropumps are widely used in microfluidics [11] and microoptics [12] however the application of pneumatic switching to microwave elements is novel. This paper will experimentally demonstrate a pneumatic switching technique on a fishnet metamaterial for the first time. Pneumatic actuation is used to tune the resonant frequency of the fishnet metamaterial by changing the metallization pattern within its unit cell, with the addition of extra elements to an initial existing structure.

2. METAMATERIAL CONCEPTS

Metamaterials are composite structures consisting of periodically repeated resonant unit cells. They are described in terms of effective parameters that represent them as equivalent homogeneous media. For the concept of effective parameters to be valid the wavelength of incident radiation should be larger than the unit cell size, so the field does not change significantly within one unit cell. As $n^2 = \varepsilon\mu$, to obtain negative refractive index both permittivity and permeability of the material have to be negative within the same frequency range.

Effective permittivity can be engineered by manipulating the metamaterial response to electric component of the field. Metals can be considered plasmas of electric charges. The response of metals to an electromagnetic field can be described by the Drude model $\varepsilon(\omega) = 1 - \omega_p^2/(\omega^2 - j\gamma\omega)$, where γ represents losses. Metals have negative dielectric permittivity for frequencies below their plasma frequency ω_p, which is usually very high (in the ultraviolet range). At microwave frequencies the permittivity of metal has very large negative values, resulting in rapid attenuation of incident wave. For metamaterial operation these values need to be reduced. Since the plasma frequency depends on concentration of charges it can be reduced to the microwave range by "diluting" the metal into array of thin wires. As electrons are confined to the wires the increase in self inductance of the wires allows many orders of magnitude reduction in plasma frequency to be achieved. However the response is observed only when the electric field is aligned with the wires.

Engineering effective permeability requires more creative approach since very few materials respond to magnetic component of the field. Negative permeability is achieved by exciting resonant circular currents in metallic loops. It is described by the Lorentz formula $\mu = 1 - (\omega_{mp}^2 - \omega_0^2)/(\omega^2 - \omega_0^2 - j\Gamma\omega)$. Here ω_{mp} is magnetic plasma frequency and ω_0 is the resonant frequency of LC circuit where the current is induced. Both depend on geometrical parameters and the distance between resonant elements. The dissipation parameter Γ is governed by the resistivity of the metal and should be small to allow the permeability to reach negative values in a narrow region around the magnetic resonance. For optimum performance of a metamaterial the magnetic resonance frequency should be slightly below the modified plasma frequency of the structure [13] to achieve similar magnitudes for effective permittivity and permeability for better impedance matching.

In case of the fishnet metamaterial structure as in Fig. 1(a) antiparallel currents forming a loop in y-z plane are induced on the metallic layers by the magnetic field passing between them, so it is essential to have two patterned metal layers to close the loop. The permeability can be controlled by changing the inductance of the slab (by altering its size p) and capacitance between the layers by using dielectric spacer of thickness t and permittivity ε_r. The effective permittivity of the structure can be controlled by the wire width w as well as spacing between the wires, which is unit cell size [3].

3. DESIGN

3.1. Design of Individual Layers

The proposed reconfigurable fishnet structure consists of a number of substrate layers. The central layer consists of the well known fishnet structure [3, 7], and a representation of the unit cell with all the geometrical parameters is shown in Fig. 1(a). The fishnet used in this study is polarization independent, due to the square shape of its slab of size p. The fishnet was fabricated by a conventional printed circuit board processes on both sides of a PCB substrate with

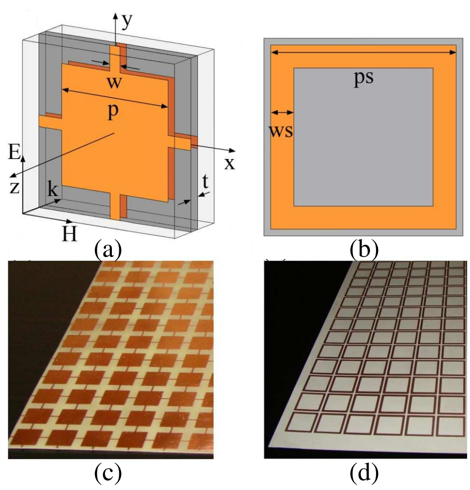

Figure 1. (a) Unit cell of the main fishnet with parameters: continuous wire width $w = 1$ mm, slab length and width $p = 11.5$ mm, thickness of dielectric $t = 0.4$ mm, cell dimensions $15 \times 15 \times 3$ mm. (b) Unit cell of additional square ring elements with parameters: size of square ring side $ps = 13.5$ mm, width of square ring $ws = 1$ mm. (c) Photograph of the fabricated fishnet structure. (d) Photograph of the fabricated sheet of the square rings.

permittivity $\varepsilon_r = 4$ and loss tangent $\delta = 0.013$ covered with copper of 17 μm thickness.

Figure 1(b) depicts the unit cell of the additional elements used to modify the unit cell geometry of the fishnet. The additional elements are square rings with a side length larger than that of the main fishnet element. Two identical layers with square rings patterned on one side only were fabricated using flexible substrate (Ultralam 3850) with a thickness of $t = 0.1$ mm, dielectric constant $\varepsilon_r = 2.9$, loss tangent $\delta = 0.0025$, and a copper thickness of 17 μm. Photographs of the fabricated periodic structures of Figs. 1(a) and (b) are shown as Figs. 1(c) and (d) respectively.

3.2. Assembling of the Layered Pneumatic Structure

Figure 2 explains the alignment of the layers and the principle of operation of the resulting reconfigurable fishnet metamaterial. The unit cell consisted of the fishnet from Fig. 1(a) placed between two additional layers of substrate patterned with square rings as shown in Fig. 1(b) with the metal patterned sides facing the fishnet. A photograph of the fabricated structure (staggered to show each layer) is shown in Fig. 2(c). The overall dimensions of each layer were close to the size of an A4 sheet, containing 14 unit cells in the x direction and 19 unit cells in the y direction. The dimensions of the structure unit cell are 0.36λ in transverse direction and 0.024λ in the direction of propagation, which are typical for fishnet metamaterials [3] The substrates were aligned so that the square rings were positioned symmetrically around the fishnet slab (Fig. 2(a)). The three layers were then sealed together around the edges of the sheets using adhesive tape. No separators were used between the layers. An outlet pipe was connected to one corner of the structure and then to a vacuum pump for pneumatic operation (Fig. 2(d)). Due to flexibility of the top substrate the inhomogeneity introduced by the pipe subsided within 1.5 cm of the connection.

3.3. Principle of Operation

In the open switch state when no vacuum is applied an air gap exists between square rings and the fishnet layer, as the flexible substrates are not perfectly flat. This small gap is sufficient to break electrical contact between the metallic elements. The combination of large area and small thickness of the structure aids in achieving a reasonably homogeneous air gap. The square rings are assumed to be at an approximate distance $g = 0.2$ mm from the fishnet (Fig. 2(b)). In this open state the only structure that exhibits a simultaneous electric

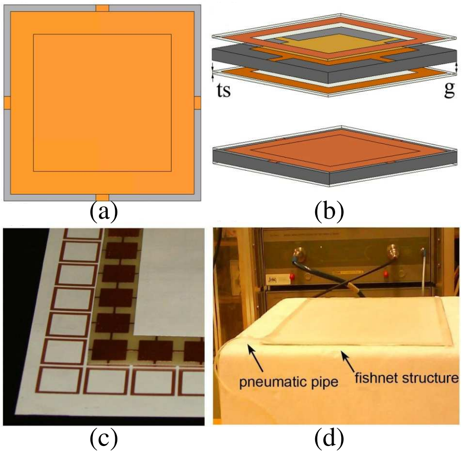

Figure 2. (a) Top view of the unit cell of the reconfigurable fishnet: thickness of substrate with square rings $ts = 0.1\,\mathrm{mm}$. (b) Side view of the same structure in switch open ($g = 0.2\,\mathrm{mm}$) and switch closed ($g = 0\,\mathrm{mm}$) positions. (c) Photograph of the fabricated reconfigurable fishnet structure showing a staggered arrangement of the layers. (d) Photograph of the sealed structure in the measurement setup.

and magnetic resonant response in the frequency range of interest is the main fishnet layer. The square rings in isolation resonate at a frequency which is out of the considered range.

By applying vacuum, the layers can be forced together to form the closed switch state, creating metallic contact between the square rings and the fishnet ($g = 0\,\mathrm{mm}$). The square rings become part of the fishnet, changing the geometry to be equivalent to a fishnet with a larger slab size. The square rings also influence the resonant response by conducting the antiparallel currents induced in the fishnet slabs, as well as exhibiting plasmonic Drude-like behavior of thin wires [3]. Also, a larger area of the central dielectric layer is involved in strong capacitive behaviour (due to the larger slab size created). This results in the shift of the resonant frequency of the closed switch structure.

4. MEASUREMENT AND SIMULATION METHOD

Transmission through the fishnet structures was measured in free space using a Wiltron 3269A Network analyzer connected to two microwave horn antennas. The area around the periphery of the fishnet was masked using a metallic aperture to prevent diffraction around the outside of the sample. The measured transmission spectra were compared to numerical simulations carried out using Ansoft HFSS software, which is based on a full-wave finite element method. All structures were simulated as periodic and infinite in the x and y directions. In the simulations, a lossy metal model of copper with a conductivity of $5.8 \times 10^7\,\mathrm{Sm}^{-1}$ was assumed.

For both experiment and simulation, the incident wave was normal to the plane of the structure, and the electric and the magnetic fields were parallel to y-axis and x-axis, respectively. Normal illumination enables optimum performance of the structure to be achieved. The structure responds only to the components of the electric and magnetic fields that are aligned to its slabs in a similar fashion to a wire grid. In the case of angular incidence only a portion of the incident power corresponding to the correctly aligned field components is coupled into the structure, thus reducing the magnitude of induced currents and subsequently the strength of the resonance until it disappears. The effect of changing the angle of incidence of the wave falling onto the fishnet structure was investigated in detail in [14].

5. RESULTS AND DISCUSSION

5.1. Switch Open Position

The resonant response of the structure in the open switch state is governed by the middle fishnet layer. Simulations show that distance of the layers with the square rings from the fishnet has a relatively minor effect on the resonant frequency of the structure. Fig. 3 demonstrates the effect of the distance g between the layers with square rings from the main fishnet. A resonant dip at around 7 GHz is seen in all curves. For smaller gaps the resonant dip deviates up to 0.1 GHz from the 7 GHz value due to increased coupling between the elements however as gap increases the resonant frequency tends to remain the same. The position of the transmission peak at 7.2 GHz where the structure is usually intended for operation remains relatively unaffected. This behaviour is an advantage for frequency tuning because it eliminates the need for precise control of the gap size.

Figure 4(a) shows the simulated and measured transmission through the reconfigurable fishnet structure for one of the switch open positions from Fig. 3. The gap was assumed to be $g = 0.2\,\mathrm{mm}$ as it provided the best fit between measurements and simulations. Good agreement between the predicted and measured positions of resonance is observed. The measured structure resonates close to 7 GHz. Higher transmission values below resonance for all experimental results can be explained by finite size of the fabricated sample as compared to infinite simulated structure. The slight deviation of the experimentally determined resonant frequency from the theoretically predicted value can be explained by a possible misalignment between the layers of the structure. Although the structure is traditionally operated in transmission mode the simulated reflection is also shown in Fig. 4 and Fig. 5.

The result confirms the hypothesis that when vacuum is not applied there is no sufficient electrical contact between the metallic elements. To ensure a total absence of contact between the layers the structure can be inflated by applying positive pressure. Even though the desired operation was already achieved without inflation, further

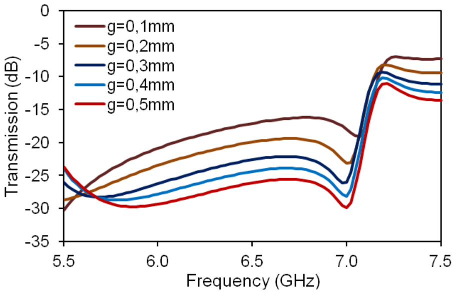

Figure 3. Simulated transmission through three layered fishnet in switch open position for different distances g.

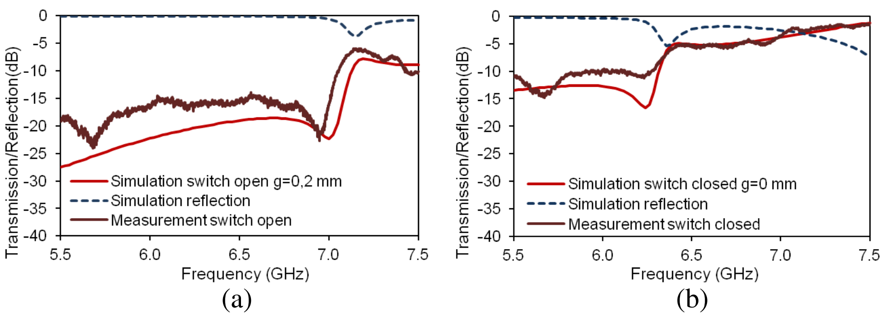

Figure 4. (a) Simulated and measured transmission through the reconfigurable three layered fishnet structure in switch open position ($g = 0.2$ mm). (b) Simulated and measured transmission through the reconfigurable three layered fishnet structure in the switch closed position ($g = 0$ mm). The dotted line represents the simulated reflection.

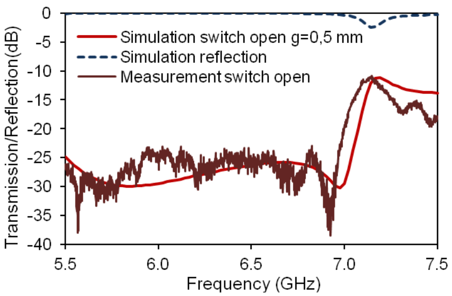

Figure 5. Simulated and measured transmission through the reconfigurable three layered fishnet structure in switch open position ($g = 0.5$ mm). The dotted line represents the simulated reflection.

tests with slightly inflated structure were conducted. The distance between the layers with square rings and the main fishnet was assumed to be $g = 0.5$ mm in this case. The transmission results are shown in Fig. 5. The structure still resonates at around 7 GHz confirming that in the switch open state the square rings have a very minor effect on the resonant frequency and affect only losses in the structure. It also confirmed that an increased gap (g) did not significantly shift the resonance frequency.

5.2. Switch Closed Position

Figure 4(b) presents the simulated and measured transmission through the fishnet structure in the switch closed position ($g = 0$ mm). Again, good agreement is observed between prediction and measurement. The resonance has shifted to around 6.2 GHz from the 7 GHz obtained in the open state. The simulated frequency response of the switchable fishnet in the switch closed position is identical to the resonant behaviour of the fishnet with a continuous slab of the size $p = 13.5$ mm [8] (same to the side length of the square rings) including the outer dielectric layers. The results support the hypothesis that when the metal square rings touch the fishnet, they form a connected conducting structure effectively changing the fishnet geometry and resulting in an increase of the slab width, and hence a lower operating frequency. Upon contact with the fishnet, the square rings impact on the circular currents, induced by the incident magnetic field, which now flow along the square rings as well as the central part of the fishnet slab. Also, due to the fact that there is continuous dielectric substrate between the fishnet cells, adding the metal ring increases the effective area of the capacitive slab and hence the overall resonant response of the structure moves to a lower frequency.

When disconnecting the fishnet structure from the pneumatic pump and allowing air to fill between the layers of the structure the metallic contacts between the square rings and fishnet were disconnected and the structure reverted to the original resonant frequency of 7 GHz. Thus negative pressure forcing metal elements against each other is essential for good electric contact. The pressure in switch closed position was 0.15 bar. The switching was performed a number of times and no noticeable shifts in the resonant frequencies of either state were observed.

5.3. Field and Current Distributions

Figures 6(a), (b) show the distribution of electric field and current on the metal surface of the middle fishnet structure in switch open position. The largest variation of the field is at 7.2 GHz, the frequency just above the resonance. The maxima of induced electric field are located at the corners of the structure. The currents flow through the middle of the fishnet slab and through the necks in the opposite direction. The points where the currents meet serve as an origin of the displacement current through the capacitive dielectric spacer to the second fishnet layer where similar currents flow in direction antiparallel to the first layer thus closing the LC loop around the magnetic field (Figs. 6(i), (j)). Figs. 6(c), (d) shows the response of the square rings at the same frequency. The charges induced along the inner contour of the ring are because of the proximity to the middle metal layer and are not caused by the resonance of the ring. Weak non resonant current flows on both layers of rings in the same direction. In the absence of the middle metallic layer no charges are induced on the rings at this frequency.

It can be seen in Figs. 6(e), (g) that once the contact between metallic elements is established in switch closed position the maximums of the electric field shifted towards the corners of the square rings. The largest variation of the field is now seen at 6.4 GHz, the frequency just above the new resonance. Such field distribution and resonant frequency correspond to the fishnet structure with larger slab size, confirming the hypothesis that square rings behave as part of the fishnet. The current on the middle part (Fig. 6(f)) is similar to the previous case, however the current on the square ring (Fig. 6(h)) is significantly different. Similarly to the electric field current on the ring appears to be a continuation of the current distribution on the middle fishnet, having large values on the side and neck areas. The current on the second layer of the square rings now flows in the direction antiparallel to the current of the first layer of the rings in agreement with the currents on the corresponding side of the middle fishnet layer.

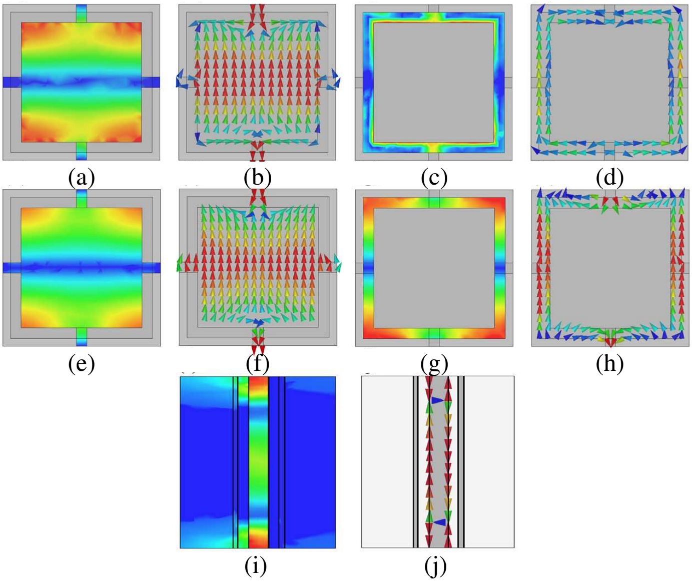

Figure 6. Electric field and current distributions for middle fishnet (a), (b), (e), (f) and square rings (c), (d), (g), (h) in switch open (a), (b), (c), (d) and switch closed (e), (f), (g), (h) positions at frequencies just above the corresponding resonances. Magnetic field (i) and current (j) distributions in y-z plane (side view) for the structure in switch open position.

5.4. Discussion

The refractive index plotted in Fig. 7 and real parts of permittivity and permeability plotted in Figs. 8(a), (b) were extracted from the simulation data [15], and show negative values for both switch positions. Drude type permittivity response of thin wires and Lorentz type permeability response of the slabs can be seen.

This illustrates that in switch closed position sufficient contact is achieved between the metallic parts and it is acceptable to consider them one metallic unit cell of differing geometry to that of the initial unit cell in switch open configuration. It is hence demonstrated that pneumatic technology can be used as a tool for uniting a number of metallic elements into a more complex conducting structure. The square ring shapes of the additional elements are more complex structure than the rectangular shorting patches used in MEMS configurations to close gaps. On each side of the presented fishnet structure, 266 elements were switched simultaneously using a single membrane with 1.5 mm spacing between square ring elements and a 0 mm gap between square ring and middle fishnet. This approach can be applied to other microwave applications where changing the metallization pattern without the addition of biasing networks which could interfere with the electromagnetic response of the metamaterial can be beneficial.

In this work, the pneumatic switching of a metamaterial structure between two resonant frequencies was demonstrated as a proof of concept. Theoretical investigations suggest that a number of square ring elements of different sizes could be employed separately or in combination, creating a multitude of operating frequencies, however, this would require the independent actuation of the square rings within a unit cell. Realization of this more complicated multi-resonant structure will require a more sophisticated, integrated actuation and control mechanism. Such a structure is currently under investigation.

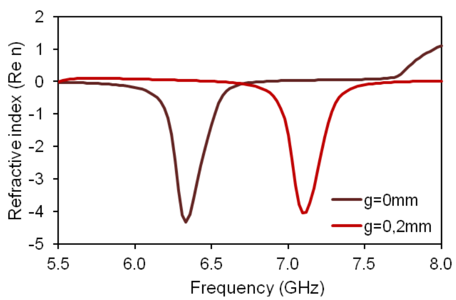

Figure 7. Refractive index extracted from simulations in switch open ($g = 0.2$ mm) and switch closed ($g = 0$ mm) positions.

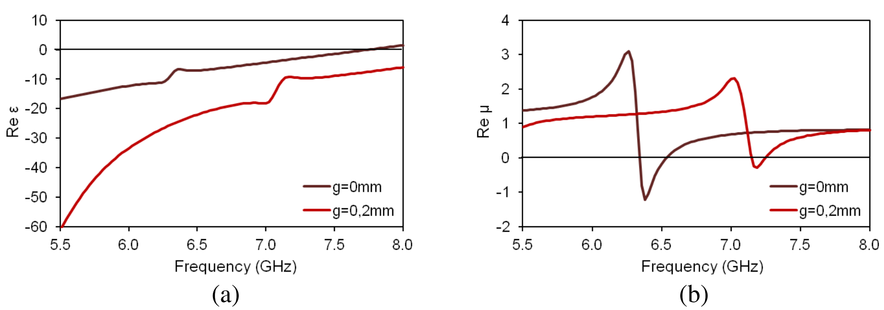

Figure 8. Effective parameters extracted from simulations in switch open ($g = 0.2$ mm) and switch closed ($g = 0$ mm) positions, (a) permittivity (b) permeability.

Another possibility is to improve control of the gap between the layers. In spite of the observation that gap has very minor effect on the resonant frequency of the structure it has significant effect on the transmitted power and controlling value of g may be useful for tuning the power level. This approach would also require an improved structural design and better control of air pressure inside the layers.

6. CONCLUSION

The design, fabrication and characterization of a reconfigurable fishnet structure consisting of three substrate layers has been presented. Pneumatic operation was applied to bring two outer layers patterned with metal square rings in contact with a middle layer, which had the form of a traditional fishnet. The potential of using pneumatic switching for uniting a number of metallic elements into a connected conducting structure has been experimentally demonstrated. The pneumatic switching modifies the geometry of the resonant elements in each unit cell. The proposed reconfigurable metamaterial structure has been realized, and operation at two different frequencies in switch open and switch closed states corresponding to different fishnet geometry configurations was confirmed. The key advantages of the demonstrated pneumatic actuation are greater flexibility in the shape and proximity of the reconfigurable elements, as well as elimination of metallic bias lines which would otherwise compromise the RF properties of the structure.

REFERENCES

1. Veselago, V. G., "The electrodynamics of substances with simultaneously negative values of ε and μ," *Soviet Phys. Uspekhi*, Vol. 10, No. 4, 509–514, 1968.
2. Shelby, R. A., D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science*, Vol. 292, No. 5514, 77–79, 2001.
3. Kafesaki, M., I. Tsiapa, N. Katsarakis, T. Koschny, C. M. Soukoulis, and E. N. Economou, "Left-handed metamaterials: The fishnet structure and its variations," *Phys. Rev. B*, Vol. 75, No. 23, 2007.
4. Valentine, J., S. Zhang, T. Zentgraf, E. Ulin-Avila, D. A. Genov, G. Bartal, and X. Zhang, "Three-dimensional optical metamaterial with a negative refractive index," *Nature*, Vol. 455, No. 7211, 376–379, 2008.

5. Driscoll, T., S. Palit, M. M. Qazilbash, M. Brehm, F. Keilmann, B. G. Chae, S. J. Yun, H. T. Kim, S. Y. Cho, N. M. Jokerst, D. R. Smith, and D. N. Basov, "Dynamic tuning of an infrared hybrid-metamaterial resonance using vanadium dioxide," *Appl. Phys. Lett.*, Vol. 93, No. 2, 2008.
6. Chen, H. T., J. F. O'Hara, A. K. Azad, A. J. Taylor, R. D. Averitt, D. B. Shrekenhamer, and W. J. Padilla, "Experimental demonstration of frequency-agile terahertz metamaterials," *Nature Photon.*, Vol. 2, No. 5, 295–298, 2008.
7. Ding, P., E. J. Liang, W. Q. Hu, L. Zhang, Q. Zhou, and Q. Z. Xue, "Numerical simulations of terahertz double-negative metamaterial with isotropic-like fishnet structure," *Photon. Nanostruct: Fundam. Appl.*, Vol. 7, No. 2, 92–100, 2009.
8. Khodasevych, I. E., W. S. T. Rowe, and A. Mitchell, "A reconfigurable fishnet metamaterial design using MEMS principle," *4th Int. Congr. on Adv. Electromagn. Materials in Microwaves and Optics, Metamaterials*, 459–461, Karlsruhe, 2010.
9. Ekmekci, E., K. Topalli, T. Akin, and G. Turhan-Sayan, "A tunable multi-band metamaterial design using micro-split SRR structures," *Opt. Express*, Vol. 17, No. 18, 16046–16058, 2009.
10. He, X., Y. Wang, J. Wang, and T. Gui, "MEMS switches controlled multi-split ring resonator as a tunable metamaterial component," *Microsyst. Technol.*, Vol. 16, No. 11, 1831–1837, 2010.
11. Jeong, O. C. and S. Konishi, "Fabrication and drive test of pneumatic PDMS micro pump," *Sensors and Actuators A*, Vol. 135, No. 2, 849–856, 2007.
12. Werber, A. and H. Zappe, "Tunable pneumatic microoptics," *Journal of Microelectromechanical Systems*, Vol. 17, No. 5, 1218–1227, 2008.
13. Ramakrishna, S. A. and T. M. Gregorczyk, *Physics and Applications of Negative Refractive Index Materials*, SPIE Press, Belligham, Washington USA, 2009.
14. Alici, K. B. and E. Ozbay, "Characterization and tilted response of a fishnet metamaterial operating at 100 GHz," *J. Phys. D: Appl. Phys.*, Vol. 41, No. 13, 135011, 2008.
15. Smith, D. R., S. Schultz, P. Markos, and C. M. Soukoulis, "Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients," *Phys. Rev. B*, Vol. 65, No. 19, 1951041–1951045, 2002.