Microwave Artificially Structured Periodic Media Microfluidic Sensor

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Abstract

In this paper, microstrip-based spiral structured artificial magnetic media (metamaterial) coupled with microfluidic channel is experimentally demonstrated for sensing applications. It is found that the resonant frequency and the amplitude changes due to dielectric loading from the introduction of chemical substances in the microfluidic channels. Different concentrations of water - methanol and water - isopropanol samples are used in the characterization of the sensor. For water - methanol mixtures, the resonant frequency shifts from 2.15 GHz to 2.0 GHz with change in dielectric constant from 25 to 75. Results show that the wave propagation in LH-media can be used for interrogation of minute volumes of samples with high sensitivity.

Introduction

Rapid characterization of chemical and biological samples is increasingly important in clinical, security, safety, drug discovery and industrial applications. Sensing approaches are needed that does not require tagging, (e.g., using fluorescent markers) in order to maintain the samples in their original form while under study. Along with rapid label-free characterization, interrogation of small sample volumes is critically needed in the areas of clinical diagnosis and drug discovery. In this paper, periodic media co-integrated with microfluidic leading to a novel RF near-field sensor is implemented to tackle these challenges. The proposed sensor is simple, cost effective, and can be used for label-free sensing and detection

Spiral structured artificial magnetic media (metamaterial) designs have been widely used in the design of compact coplanar waveguides (CPW) and microstrip-based circuit topologies. Recently, split-ring based metamaterial structures that are edge-coupled to a microstrip line have been used in the sensing of biomolecules [1]. In this structure, the interrogation signal (RF) edge couples from a microstrip transmission line to a ring resonator. The biomolecules are made to bind onto the ring resonator. A direct approach of interrogation will be desirable which is more compact and provides improved sensitivity and yet still simple to fabricate and implement. To meet this goal, in this paper, metamaterial structure that is integral part of the microstrip line is employed for sensing application. A spiral based metamaterial transmission was recently introduced, [2 – 3], and this design is implemented here for sensing applications.

In spiral based metamaterial transmission lines, the periodic arrays of the spiral structure employ left-handed (LH) propagation properties and support backward waves at their fundamental resonance [2]. Motivated by the wave propagation phenomenon of this medium, a microfluidic sensor that interrogates samples in the near-field region is attractive to achieve high sensitivity using low-volumes of samples. This sensor is designed and implemented for different resonant frequencies and results from one of the design are presented here. Microfluidic channels and the metamaterial based transmission lines are co-integrated on a single substrate to achieve high sensitivity. The proposed sensor consists of spiral resonators positioned in series forming a double and triple spiral LHMs transmission line structure fabricated on a commercially available printed wiring board. The micromachined fluidic channel is designed and fabricated on the top layer of the spiral structure signal strips. The proposed method can provide the benefit of faster, easier, low-cost, high-throughput, and more convenient analysis of chemical substances and biological specimens at RF frequencies.

Design and Fabrication

Fig. 1 shows the layout of an artificially structured periodic media to be used for the design of a sensor. It is composed of two single spirals connected in series on the front side and a solid ground plane on the back side of the board. This unit cell forms a double spiral resonator with dimensions d_x = 6.4 mm and d_y = 3.2 mm. The periodic analysis of the double spiral unit cell shows that the structure supports backward waves as LH media at their fundamental resonance [3]. Fig. 2 shows a fabricated metamaterial transmission line based on triple cells of double spiral components. It was fabricated on RT/Duroid® 5880 substrate having dielectric constant ε_r = 2.2 and thickness of 1.58 mm using conventional microfabrication approaches. The measured and simulated, using the Ansoft HFSS®, frequency responses are shown in Fig. 3. These results are before the integration of microfluidic layer. The simulated and measured responses match very closely and the measured insertion loss is approximately -1 dB for this structure. Upon fabrication of microfluidic layer on top of this structure, the resonance frequency shifts to lower frequency as discussed ahead.

Microfluidic channels were fabricated from elastomer polydimethylsiloxane (PDMS) using a SU8-2000 mold. A 100 μm thick layer of SU8-200 was spin coated on a thin polyimide (PI) film (50 μm). The polyimide film in turn was attached to a Si wafer during spin coating. SU-8-2000 has better adhesion with PI than bare Si-wafer. A prebake process, UV lithography, postbake, and etching are performed to fabricate the mold (master). To form the microfluidics channels, Polydimethyl Siloxane (PDMS) elastomer is used that is a two-part resin system containing vinyl groups and hydrosiloxane groups. PDMS is a soft material and it can easily be separated from the SU-8 master, leaving the master intact for the fabrication of additional microfluidic channels. The PDMS microfluidic channel is designed in S-shape following the spiral line to couple with locations having stronger electric and magnetic fields on the spiral structures. An example fabricated microfluidics channel made from PDMS is shown in Fig. 4. The depth of the microfluidic channel is 100 μm.

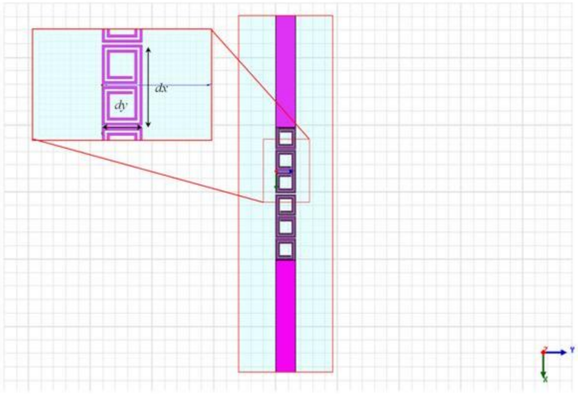


Fig. 1 Model of the artificially structured periodic media based double spiral.

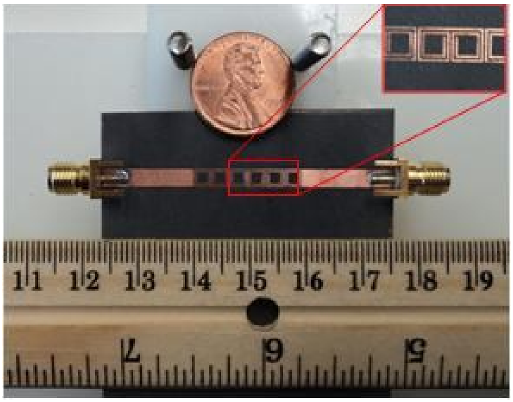


Fig. 2 Fabricated Metamaterial microstrip transmission line based double spiral structure.

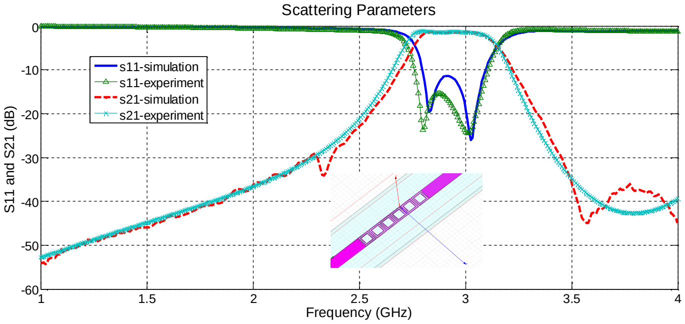


Fig. 3 Simulated and measured frequency responses of the metamaterial microstrip technology based spiral structure. The simulated structure model is depicted in the inset.

Instead of directly attaching the mold to the circuit board, a thin film of PI (50 μm) was introduced between the PDMS channels and the copper traces. This film was attached to PDMS using a siloxane adhesive. Polyimide acts as a chemical barrier between the copper traces and the liquid sample in the channels. Although this reduces the sensitivity, but it helps prevent any damage to the copper traces if harsh chemicals are to be interrogated. Mounting of the PDMS onto the metamaterial microstrip structure loads the circuit and changes the S-parameters of Fig. 3. Simulated and measured S-parameters of this loaded structure are shown in Fig. 5 and they match very closely. Slight difference may be due to the dielectric properties of the PDMS used in the simulation of the structure.

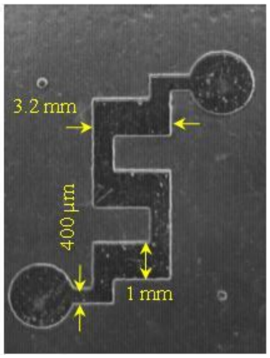


Fig. 4 PDMS microfluidic channels (a) photograph showing the close up (b) optical photograph of the channel before PI film attachment.

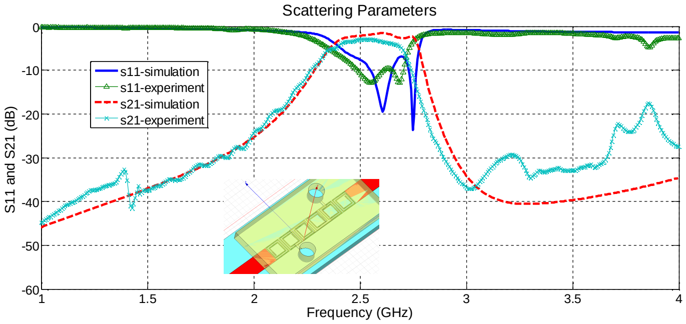


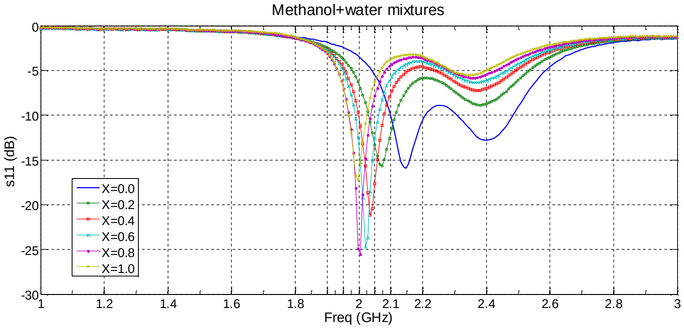
Fig. 5 Simulated and measured frequency responses of the fabricated metamaterial RF device attached with PDMS microfluidic channel on the top. The simulated structure model is depicted in the inset.

RF Measurements and Discussions

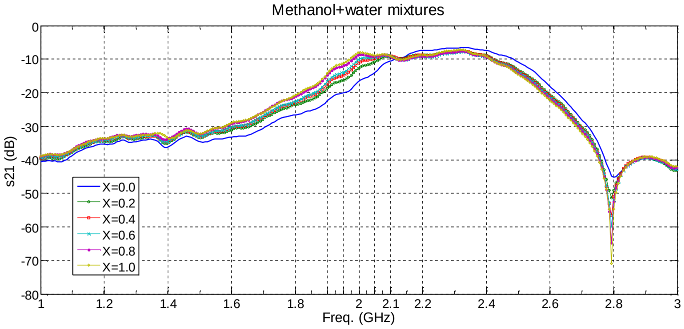
Preliminary tests were carried out with the microfluidic channel filled with different concentrations of 2-propanol-water and methanol-water sample mixtures. The solutions were prepared by molar fraction from Mallinckrodt Chemicals and de-ionized water at the concentration index, X = 0, 0.2, 0.4, 0.6, 0.8, and 1.0 at the room temperature. During the measurements, the sample was allowed to continuously flow using a syringe pump. Teflon tubing (inner diameter = 0.8 mm, outer diameter = 1.6 mm) was attached to the PDMS using epoxy. A syringe-30mL was used for sample handling. A Vector Network Analyzer was used to measure the scattering parameters of the loaded transmission line. Sufficient amount of liquid was allowed to flow through between samples to remove any residue in the microfluidics channels between the measurements. The transmission (S21) and reflection (S11) scattering parameters were measured for all the sample solutions. A close-up view of the measurement setup is shown in Fig. 6.

Fig. 7 and Fig 8 show the measured scattering-parameters of different concentrations of water - methanol and water - 2-propanol liquid solutions. The transmission properties and the resonant frequency (f_r) shifts depending upon the dielectric properties of the sample in the microfluidic channel. The shift in frequency indicates the effective dielectric constant and the change in amplitude indicates the loss-tangent of the liquid sample. Minimum value of the S11 parameter was used as the reference point of frequency measurement. This frequency can easily be measured from the phase plot of S11.

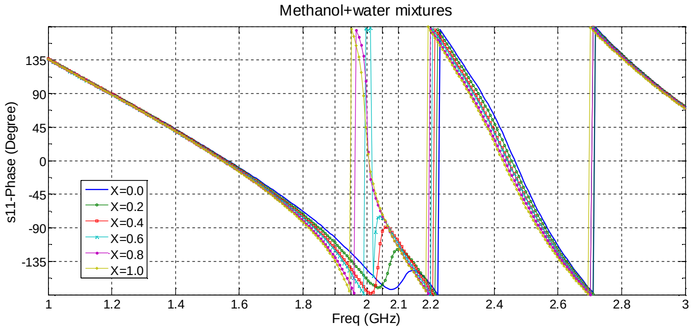
Fig. 6 Fabricated Metamaterial RF device with PDMS microfluidic channels attached.



(a) Measured insertion losses



(b) Measured return losses



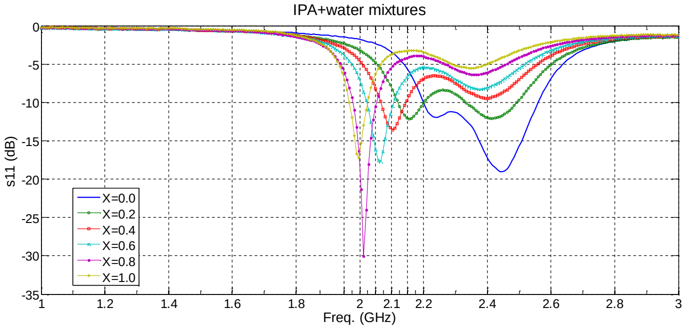
(c) Measured phase insertion losses

Fig. 7. Measured scattering parameters under test corresponding different concentrations of water - methanol mixtures

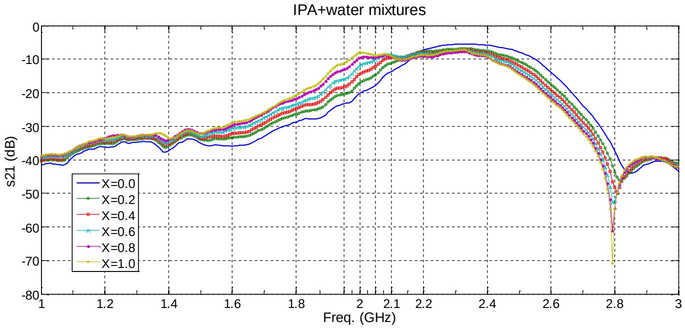
The mixtures in various molar fractions can be translated approximately to the dielectric constant, ε´ by the Davidson-Cole equation that is expressed by [4].

$$\epsilon^*(\omega) = \varepsilon_\infty + \Delta\varepsilon/(1 + i\omega\tau)^\alpha \tag{1}$$

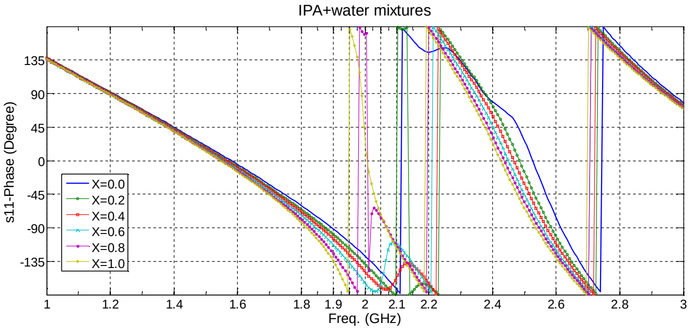
where ε^* is the complex permittivity at an angular frequency ω, ε is the permittivity at $\omega \rightarrow \infty$, Δε is the relaxation increment, and τ is the relaxation time. Referring to the data from T. Sato *et al.* [3], the dielectric constants of water-methanol mixtures in various frequencies can be investigated by Eq. (1). Fig 9 shows the dielectric constant (ε´) and loss tangent (tan-δ) of water-methanol solutions for various concentrations based on the above equation. The results show that the dielectric constant and loss-tangent of methanol are approximately 27 and 0.65 at 2 GHz, respectively. Also for DI-water, these values are approximately 80 and 0.12, respectively. These values match very closely with those reported by J. Barthel *et al.* [5] and C. Oliver Kappe *et al.* [6]. These were used in the translation of concentration to dielectric constant values.



(a) Measured insertion losses

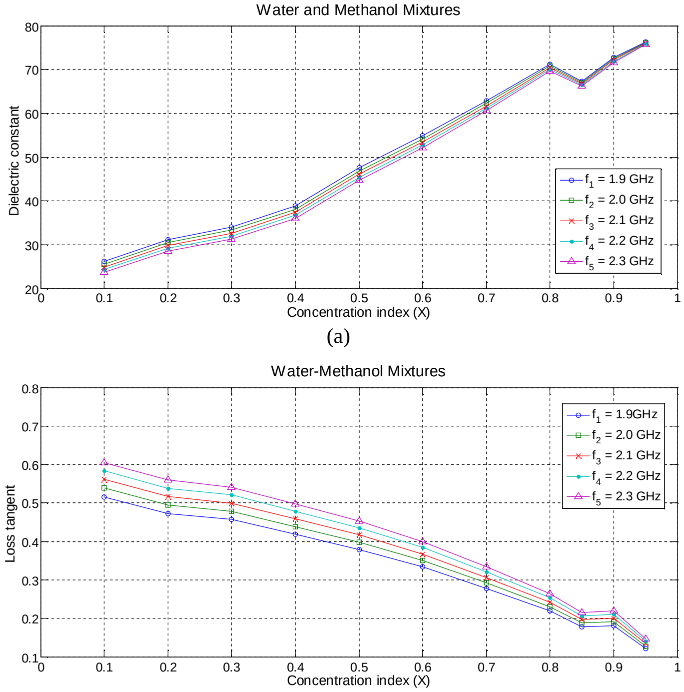


(b) Measured return losses



(c) Measured phase insertion losses

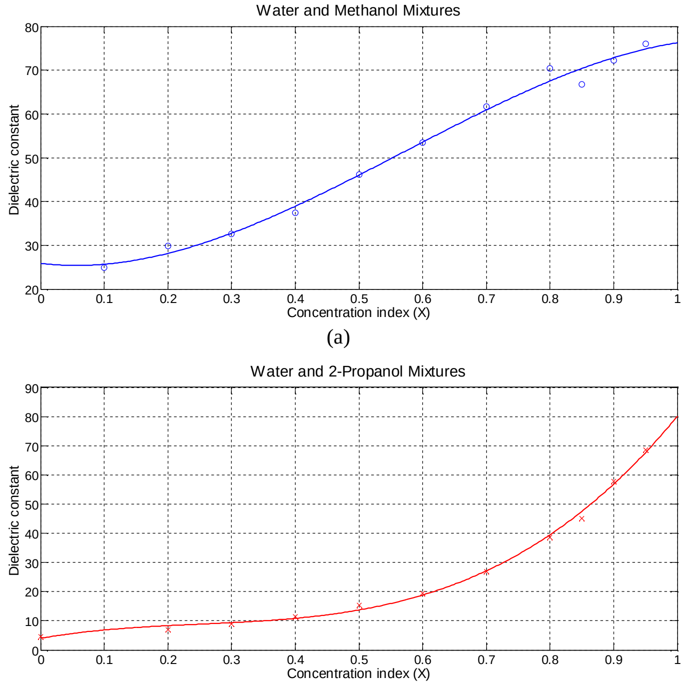
Fig. 8. Measured scattering parameters under test corresponding different concentrations of water - 2-propanol mixtures



(a)

(b)

Fig. 9. Dielectric constant and loss tangent of water-methanol mixtures at various frequencies based on the data from [3].



(a)

(b)

Fig. 10. Dielectric constant of water-methanol (a) and water-2-propanol (b) mixtures by cubic curve fitting based on the data from [3].

Referring from the study by J. Barthel *et al.* [5], dielectric relaxation parameters of 1-propanol and 2-propanol are almost the same and are readily available. For first order approximation, the dielectric relaxation parameters of water -1-propanol in [4] are used in Eq. (1) for the dielectric relaxation parameters of water-2-propanol samples used in this paper. As a result, the correlation between dielectric constants of water –methanol and water-2-propanol mixtures with different concentration index can is plotted in Fig. 10. After converting the unit from the concentration index to dielectric constant, the variation of the frequency, f_r with approximate dielectric constant (ε´) of water-methanol and -2-propanol mixtures can be expressed in Fig. 11. This shows a significant improvement in sensitivity as compared to data presented in ref. [7] for similar liquid mixtures. Furthermore, the circuit is simple to design, is compact and easy to integrate with microfluidic channels.

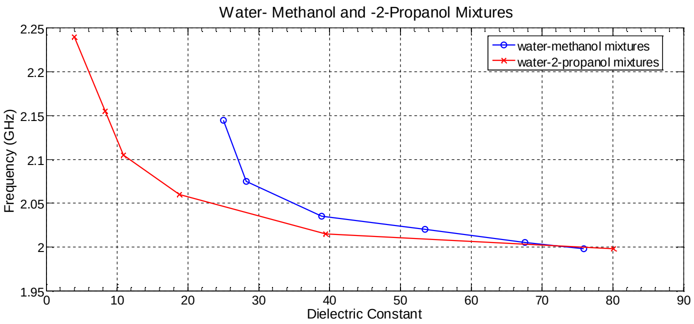


Fig. 11. Change in the resonance frequency, S_{11} (f_r), with approximate dielectric constant of water –methanol and water-2-propanol mixtures.

Conclusions

A novel microstrip-based metamaterial transmission line coupled with microfluidic channel is demonstrated for sensing of micro-liter volume of samples. The fluidic channels were routed directly above the locations on the spiral where the fields are strong in order to achieve high sensitivity. For methanol-water mixture, the resonant frequency shifts from 2.15 GHz to 2.0 GHz with change in dielectric constant from 25 to 75. For water-2-propanol mixture, the resonant frequency shift from 2.25 to 2.0 with dielectric constant change from 4 to 80. Further improvements in sensitivity can be made by using a very thin chemical barrier PI layer between the copper traces and the microfluidic channels. Results of this paper show that LH-media can be used in making a sensor having very high sensitivity. Further improvements can lead to sensing of nano- to pico-liter sample volumes. The sensor can be used for sensing of various types of chemical and biological agents both in liquid and solid form. Furthermore, the frequency band of interrogation can be designed to sense specific samples in order to achieve high specificity along with high sensitivity.

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