Microfluidic as Liquid Lens for THz Reconfigurable Antenna and Gain Enhancement With Sensing Application

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Research Article

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Microfluidic as liquid lens for THz reconfigurable antenna and gain enhancement with sensing application

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***Abstract* — the lens plays important role in the dielectric resonator antenna (DRA) for increasing the bandwidth and directivity. Also, the liquids like water and ethanol can be noticed for developing the DRA for THz application. In addition, the liquids are interesting because the level and quality of material can be used for designing reconfigurable antenna. For the THz spectrum, the liquids can be combined with antenna and microwave devices by Microfluidic technology. In this paper, the suggested antenna is used to enhance the various factors of the antenna and the filling ratio of the channels is noticed to provide reconfigurable antenna. The slot antenna with split ring resonator and meandered feed is used as the basic antenna to provide high Q-factor. Moreover, the results show that this novel structure can be used as sensor for material detecting which is used to recognize various types of liquids by determining the sensitivity of the sensor in the range of 0.5 to 1 THz. The proposed sensor is examined for pure water, ethanol and gasoline based on the 2nd order model of Debye.**

Index Terms **– antenna; Terahertz; microfluidic; Lens; reconfigurable**

I. Introduction

Various methods have been suggested to design reconfigurable antenna for microwave and THz application [1-2]. Some methods are electrical, such as PIN diodes [3] and varactor capacitors [4]. Some methods are physical, such as using micro-switches [5] and other types of these antennas are based on materials such as the use of ferrites [6], graphene [7] and liquid crystals [8]. But each of these methods has their own drawbacks and advantages, for example, the use of electrical methods requires separate excitation for PIN diode or varactor [9, 10]. And in physical methods, an external force needs to activate the switch. For using materials in a reconfigurable antenna, manufacturing problems are often a challenge.

On the other hand, we should notice that in the design of antennas, especially DRA dielectric antennas, the dielectric element plays an effective role in increasing the antenna gain and bandwidth and also miniaturization [11, 12]. Moreover, the effective wavelength of microstrip antennas is proportional to the permittivity of the substrate [13]. Therefore, the use of substances such as water and alcohol, which have a high permittivity, causes great size reduction. So, recently extensive studies have been done on this type of liquid dielectric antennas [14]. One of them was the design of wideband monopole antenna with liquid dielectric in 2006 [15]. In recent years, several models of DRA antennas with a liquid dielectrics and circular polarization have been proposed for wireless applications [16].

In addition, the THz antenna technology has been developed for various goals such as cancer detection [17] and antenna with different forms have been developed of patch antenna with photonic crystal [18], dipole antenna [19], slot antenna [20], and Yagi antenna [21-22]. However, to detect material under test for the THz spectrum using metasurface [23] and absorbers [24] are more interesting than antenna. Furthermore, the microfluidic technology has been used for transferring material [25] which can be noticed for sensing and material detection [26-27] and also it can be used for making a lens because of the higher refractive index of liquids such as water.

Moreover, the reconfigurable antennas that can work at multiple frequencies are essential to reduce operating costs in the communications industry. So recently research has been done for using liquid dielectric as a reconfigurable antenna based on a micro pump for controlling the water level [28]. In addition, Using suspended nanoparticles (emulsion) by exciting with an external field, in which a special electric field or magnet can be applied to the liquid dielectric [29,30] , and as a result, the polarization of the particles causes a change in the electrical and magnetic conductivity, permittivity and permeability and it can be interesting for future studies [31].

So, based on the previous researches, in this paper a combination of the microfluidic and THz antenna technology is considered as technique for controlling the antenna behavior including directivity, bandwidth and operation frequency. In this study, the slot antenna is developed for THz application and then liquid dielectric load based on microfluidic is added to the basic antenna by placing the micro channel over the antenna surface. This antenna shows reconfigurable characteristic by changing the volume of liquids in micro channels. In addition, it can be used for material recognition and in this study, the water, ethanol and gasoline are tested.

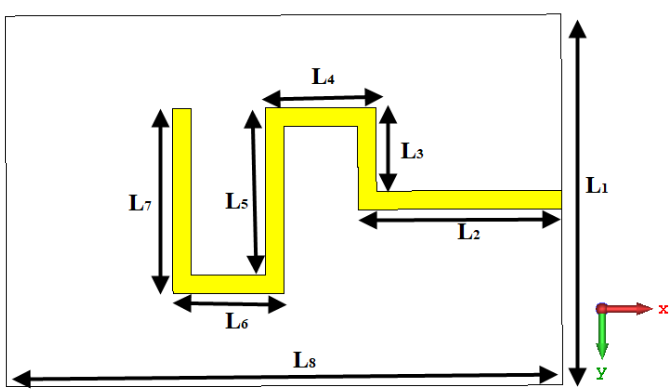
II. The antenna design and modeling

The slot antenna is considered as the basic antenna (step 1) which is excited by meandered feed line with the total length and width of 410 and 10 µm. The result shows this antenna has wide bandwidth and low Q-factor. So, in the second step (step 2) a split ring resonator is added to basic antenna. It reduces the bandwidth of antenna and increases the Q-factor. Finally, the micro channel is placed over the proposed antenna to pass liquid for either enhancing the antenna directivity and bandwidth or detecting material as a sensor in the step 3.

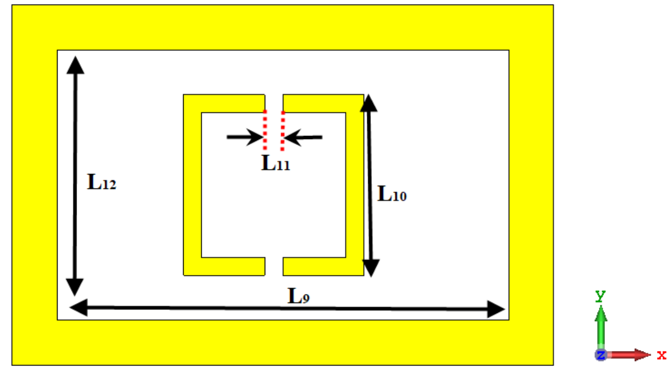
This antenna is excited by a waveguide port which plays the role of photo-mixer and the simulations have been done with CST microwave studio as a full wave software with open and space boundary for every direction. The lossless quartz with permittivity of 3.75 and the thickness of 10 µm is used as the substrate of this antenna and the meandered feed line is placed under the substrate.

A rectangular aperture is made on the ground layer of antenna. Then the SRR is pinpointed in the aperture for concentrating energy in the antenna for reducing bandwidth and Q-factor. Apparently, the gaps in the SRR can make hot spot for trapping energy. The gold is used for metal layer with the height of 0.1 um. At last, a thin film of PDMS (polydimethylsiloxane) with permittivity of 2.3 is placed on the split ring with the thickness of 2 µm that demands for real experimental fabrication.

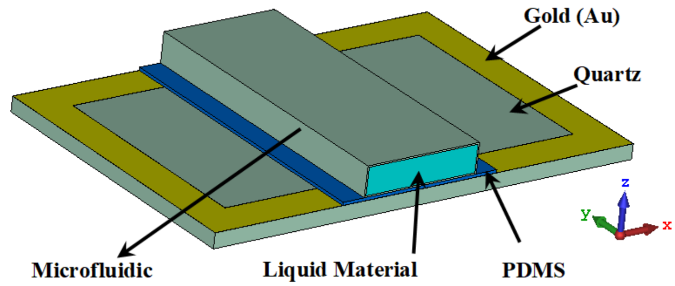
The microfluidic with height and width of 18 and 78 µm are placed over the PMDS layer. The lossless silicon is selected for the proposed micro channel with permittivity of 11.9. The Fig.1 (a) shows the proposed antenna ground layer with the SRR and the feed line is shown in Fig.1 (b). The 3D view of antenna and microfluidic placement is presented in Fig.1(c) and all dimensions of the proposed antenna are L_1 = 200 µm, , L_2 = 100 µm , L_3 = 55 µm , L_4 = 40µm , L_5 = 100 µm , L_6 = 40 µm, L_7 = 100 µm , L_8 = 300 µm , L_9 = 250 µm , L_{10} = 100 µm , L_{11} = 18 µm and L_{12} = 150 µm .



(a)



(b)



(c)

Fig.1 the geometry for the proposed antenna (a) feed line (b) the ground layer with SRR (c) placement of the Microfluidic over the ground layer

III. Discussions and Results of the antenna

The return loss of the antenna in the Step 1and 2 are checked and presented in Fig.2 in the range of 0.5 to 1 THz. As shown here, in the step 1, the antenna bandwidth in absence of the SRR covers 0.75 to 0.822 THz and it is about 29 %. In this case, the minimum value of the return loss is -18 dB. The Q-factor of the antenna can be obtained by Eq.1 where the f_0 is the operation frequency. The Q-factor for this case is about 16.8, but when the SRR is added to antenna ground, the antenna bandwidth is reduced to 14.7%. In this case the minimum value return loss is -24 dB and antenna Q-factor is 39.1.

$$Q = \frac{f_0}{BW_{3dB}} \tag{1}$$

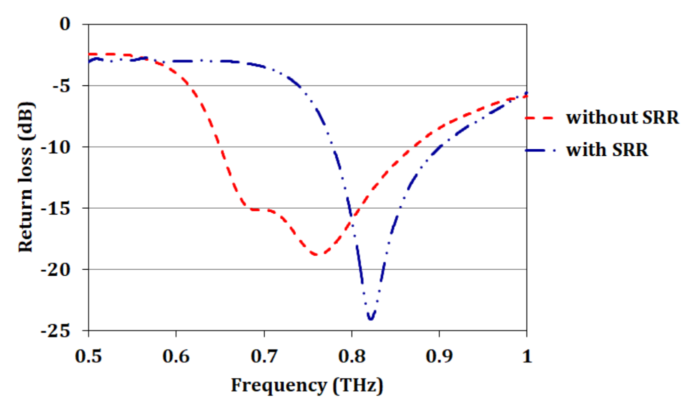


Fig.2 the return loss of the antenna in presence and absence of the SRR

The current distribution for the proposed antenna is presented in Fig.3 at 0.82 THz. As shown in Fig.3, the feed

line coupled with the SRR and the current makes a loop in SRR and also the field concentrates in the SRR which causes the higher Q-factor. On the other hand, as shown in Fig.2, the antenna without SRR has lower frequency because the feed line effective length is longer but when the SRR interacts with the feed line, it reduces the effective length, and therefore a frequency shift to 0.82 THz is visible.

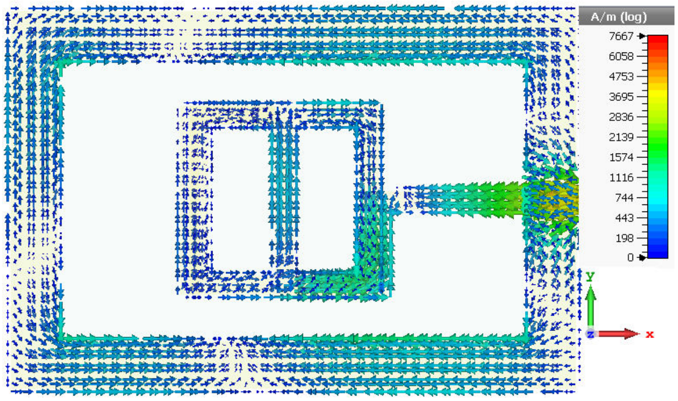


Fig.3 the antenna current distribution at 0.80 THz

To realize the effect of the gaps on the antenna Q-factor, the gaps width (L_{11}) is checked for 2 to 18 µm. As shown in Fig.4, the antenna with larger gaps has higher Q-factor, or in other words, the return loss (antenna matching) improved and it reduces to -31 dB for L_{11} = 18 µm.

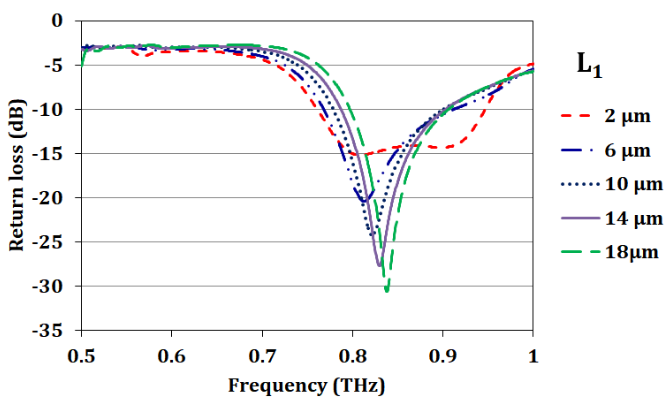


Fig.4 the return loss of the antenna for various SRR's gaps size

Recently various studies have been done for extracting the permittivity of alcohol [32-35], gasoline [34] and water [36-37] in the THz spectrum in the range of 0.5 to 2 THz. The Debye second order is used for modeling the liquid material in the THz spectrum [34, 38-40]:

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_2}{1 + i\omega\tau_1} + \frac{\varepsilon_2 - \varepsilon_\infty}{1 + i\omega\tau_2} \qquad (2)$$

The ε_∞, ε_S, ε_2, τ_1 and τ_2 are temperature dependent of high frequency permittivity, static dielectric constant, intermediate frequency limit, slow relaxation time, and fast relaxation time.

Table.1 2nd order Debye model coefficients for several types of alcohol and water

	ε_∞	ε_S	ε_2	τ_1[Ps]	τ_2[Ps]
water	**3.23**	**78.3**	**5.29**	**7.92**	**0.182**
ethanol	**2.12**	**24.35**	**4.44**	**163**	**8.97**
Gasoline	**1.96**	**2.36**	**2.06**	**3.18**	**0.05**

The real and imaginary part of the permittivity of the pure water, ethanol and gasoline are presented in Fig.5 which is used in the microfluidic channel for sensing.

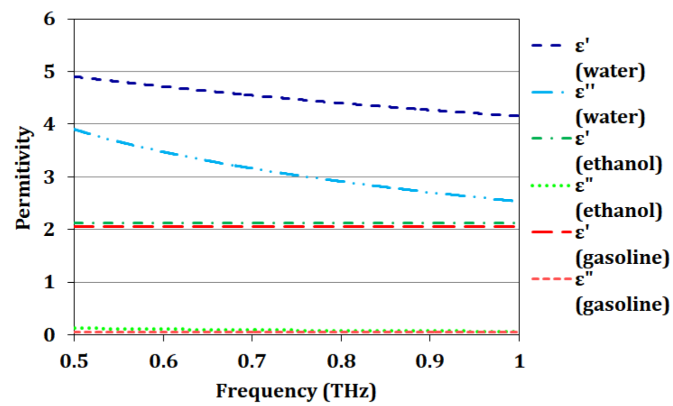


Fig.5 the real and imaginary permittivity of the water , ethanol and gasoline

The return loss of the antenna for the pure water, ethanol and gasoline are compared with the vacuum channel for L_{11} = 18 µm. By filling the channel with the liquid, the operation frequency shifts to lower frequency and in addition, the loss which is made by the imaginary part of the liquid impact on the level of the return loss where the return loss for the proposed empty sensor channel is -33 dB and this value is changed to -31dB for the gasoline and ethanol and the water is known as a lossy material thus the return loss value is obtained -22 dB at 0.8 THz.

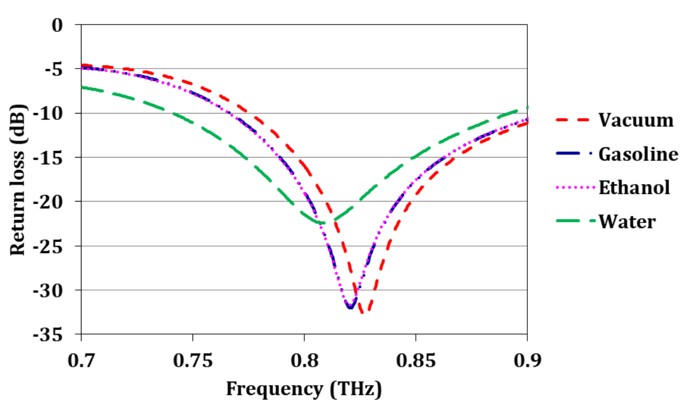


Fig.6 the return loss of the antenna for various material for sensing

The comparisons between three materials are presented in the Table.2. The Q-factor, BW, FOM and sensitivity are considered for recognizing the material in the microfluidic

channel. For calculating the sensitivity and FOM the Eq.3 and 4 can be used where the Δf is the frequency shift, Δn is the refractive index variation and the FWHM is Full width at half maximum of the return loss.

$$S = \frac{\Delta f}{\Delta n} \quad (3)$$

$$FOM = \frac{S}{FWHM} \quad (4)$$

Table.2 comparing the sensor with different materials

	Q-factor	BW	FOM RIU^{-1}	Sensitivity (GHz/RIU)
Gasoline	**86.36**	**17.15%**	**1554**	**14.77**
Ethanol	**86.84**	**17.31%**	**1534**	**14.58**
Water	**23.1**	**18.49%**	**441**	**15.44**

As shown in Table.2, the material under test can be recognizing by their effect on antenna parameters. Here, the water makes a great frequency shift, so despite of higher Δn, it has sensitivity of 15.44 GHz/RIU) , but because of wide bandwidth and lower Q-factor, the FOM shows reduction in comparison the ethanol and gasoline.

As a result, Fig.6 shows that antenna with filled micro channel by water has wider bandwidth in comparison with gasoline and ethanol. Thus this material can be used to develop this antenna by adding a few new channels to the surface of the antenna. The implementing three channels over the proposed antenna filled with water or vacuum is presented in Fig.7. So, here there cases are selected for examining the effect of the water on antenna directivity, bandwidth and frequency shift. In the first case all channel are filled by water. In the second case, the Ch.1 is assumed vacuum and only Ch.2 and Ch.3 are filled by water. Finally in the third case, only the Ch.2 is filled by water.

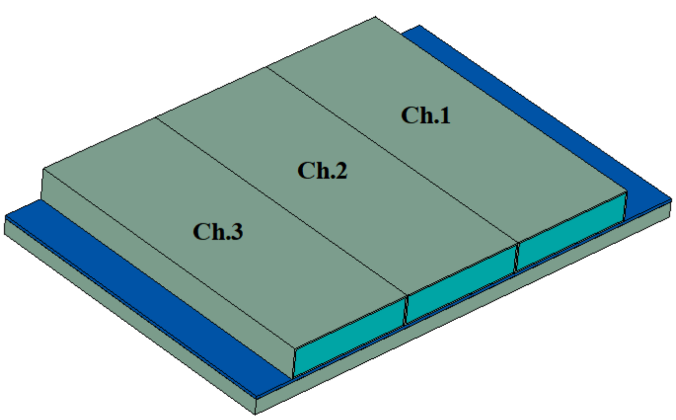


Fig.7 the implementing three channels over the proposed antenna filled with water or vacuum

The return loss of the antenna for three cases is presented in Fig.8. As shown in Fig.8, the antenna operation frequency shifts to from 0.8 to 0.73 THz by increasing the volume of the water in the channel, but water loss reduces the Q-factor of the antenna. On the other hand, the bandwidth of antenna increases from 18.65% to 49% from the case 1 to case 3.So for THz wireless application, for increasing the band width of the antenna, the liquid dielectric can be used as a solution. Moreover, as this antenna has reconfigurable characteristic to allocate special frequency for sending and receiving difference volume of the liquid can be used.

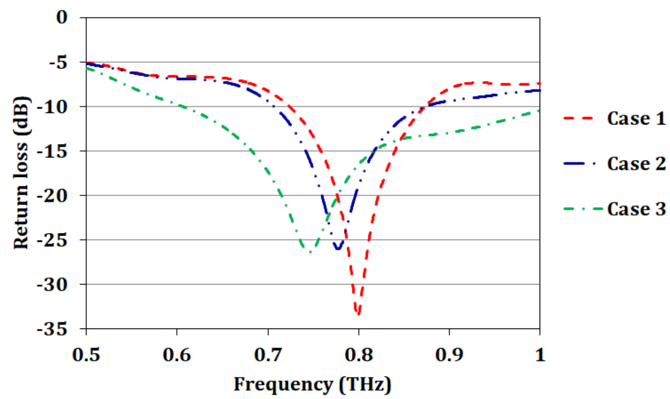


Fig.8 return loss of the antenna for three cases with various volume of water in channels

The directivity of the antenna in three cases are presented in Fig.9 and for the case 1 , the antenna directivity is 4.69 dBi and the antenna directivity increases to 5.22 dBi for the case 2 when the Ch.2 and Ch.3 are filled by water. When all channels are field by the water, the directivity increases to 5.43 dBi.

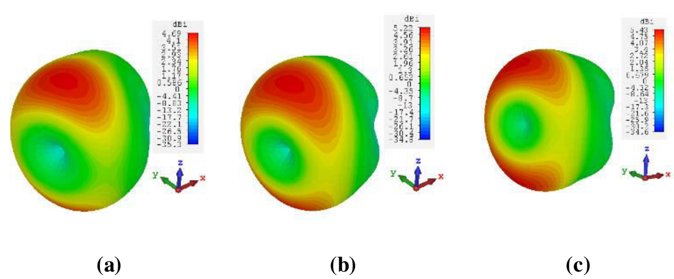


Fig.9 the directivity of the antenna for three cases (a) case 3: Ch.2 is filled (b) case 2 : Ch.2 and Ch.3 are filled (c) case 1: all channel filled

IV. Conclusion

In this paper, combination of the microfluidic structure with slot antenna was considered for sensing and recognizing the pure water, ethanol and gasoline based on the frequency shift and Q-factor. In addition various topologies of the micro channel were suggested to use the microfluidic technique with water for increasing the antenna bandwidth and gain besides designing a reconfigurable antenna in the THz spectrum. Therefore, combining the microfluidic technique and antenna can be developed for sensing and communication application at the same time.

References:

[1] Heydari, Samaneh, Kioumars Pedram, Zeeshan Ahmed, and Ferdows B. Zarrabi. "Dual band monopole antenna based on metamaterial structure with narrowband and UWB resonances with reconfigurable quality." *AEU-International Journal of Electronics and Communications* 81 (2017): 92-98.

[2] Kazemi, Fatemeh. "Dual band compact fractal THz antenna based on CRLH-TL and graphene loads." *Optik* 206 (2020): 164369.

[3] Tripathi, Shivesh, Nagendra P. Pathak, and Manoranjan Parida. "A dual feed PIN diode based switchable multiband planar meandered antenna for intelligent transportation system application." *International Journal of RF and Microwave Computer-Aided Engineering* 29, no. 11 (2019): e21936.

[4] Row, Jeen-Sheen, and Jia-Fu Tsai. "Frequency-reconfigurable microstrip patch antennas with circular polarization." *IEEE Antennas and Wireless Propagation Letters* 13 (2014): 1112-1115.

[5] Haupt, Randy L., and Michael Lanagan. "Reconfigurable antennas." *IEEE Antennas and Propagation Magazine* 55, no. 1 (2013): 49-61.

[6] Lou, Qun, Rui-xin Wu, Fan-guang Meng, and Yin Poo. "Realizing frequency reconfigurable antenna by ferrite-loaded half-mode SIW." *Microwave and Optical Technology Letters* 59, no. 6 (2017): 1365-1371.

[7] Dragoman, Mircea, Dan Neculoiu, Alina-Cristina Bunea, George Deligeorgis, Martino Aldrigo, D. Vasilache, Adrian Dinescu et al. "A tunable microwave slot antenna based on graphene." *Applied Physics Letters* 106, no. 15 (2015): 153101.

[8] Anil Kumar, Tirunagari, Yalavarthi Usha Devi, Boddapati TP Madhav, Sarat K. Kotamraju, and Vullanki Rajesh. "High gain flexible liquid crystal polymer based 8-element printed antenna for millimetric wave applications." *International Journal of RF and Microwave Computer-Aided Engineering* 29, no. 7 (2019): e21744.

[9] Seo, Dongcheol, and Youngje Sung. "Reconfigurable square ring antenna for switchable circular polarisation." *Electronics Letters* 51, no. 6 (2015): 438-440.

[10] Kim, Ilkyu, Byung-chul Park, and Jeong-Hae Lee. "Varactor diode integrated dipole-EBG base-station antenna: Enhancing tilted radiation pattern." *Microwave and Optical Technology Letters* 57, no. 8 (2015): 1794-1799.

[11] Hu, Peng Fei, Yong Mei Pan, Kwok Wa Leung, and Xiu Yin Zhang. "Wide-/dual-band omnidirectional filtering dielectric resonator antennas." *IEEE Transactions on Antennas and Propagation* 66, no. 5 (2018): 2622-2627.

[12] Pedram, Kumars, Mohammad Naderi, Fereshteh Sadat Jafari, and Ferdows B. Zarrabi. "Compact quad-band second harmonic antenna based on metamaterial DRA load." *Microwave and Optical Technology Letters* 61, no. 8 (2019): 1938-1944.

[13] Wong, Kin-Lu. *Compact and broadband microstrip antennas*. Vol. 168. John Wiley & Sons, 2004.

[14] Song, Chaoyun, Elliot L. Bennett, Jianliang Xiao, Tianyuan Jia, Rui Pei, Kwai-Man Luk, and Yi Huang. "Passive beam-steering gravitational liquid antennas." *IEEE Transactions on Antennas and Propagation* 68, no. 4 (2019): 3207-3212.

[15] Fayad, H., and P. Record. "Broadband liquid antenna." *Electronics Letters* 42, no. 3 (2006): 133-134.

[16] [Ren, Jian, Zhao Zhou, Zhao Hui Wei, Hao Ming Ren, Zhe Chen, Ying Liu, and Ying Zeng Yin. "Radiation Pattern and Polarization Reconfigurable Antenna Using Dielectric Liquid." *IEEE Transactions on Antennas and Propagation* (2020).

[17] Poorgholam-Khanjari, Shima, and Ferdows B. Zarrabi. "Reconfigurable Vivaldi THz antenna based on graphene load as hyperbolic metamaterial for skin cancer spectroscopy." *Optics Communications* 480 (2021): 126482.

[18] Nejati, Ameneh, Ramezan Ali Sadeghzadeh, and Fatemeh Geran. "Effect of photonic crystal and frequency selective surface implementation on gain enhancement in the microstrip patch antenna at terahertz frequency." *Physica B: Condensed Matter* 449 (2014): 113-120.

[19] Sadeghzadeh, Ramezan Ali, and Ferdows B. Zarrabi. "Metamaterial Fabry–Perot cavity implementation for gain and bandwidth enhancement of THz dipole antenna." *Optik* 127, no. 13 (2016): 5181-5185.

[20] Kazemi, Fatemeh. "High Q-factor compact and reconfigurable THz aperture antenna based on graphene loads for detecting breast cancer cells." *Superlattices and Microstructures* 153 (2021): 106865.

[21] Poorgholam-Khanjari, Shima, Ferdows B. Zarrabi, and Saughar Jarchi. "Compact and wide-band Quasi Yagi-Uda antenna based on periodic grating ground and coupling method in terahertz regime." *Optik* 203 (2020): 163990.

[22] Zarrabi, Ferdows B., Mir Mohsen Seyedsharbaty, Zeeshan Ahmed, Afsaneh Saee Arezoomand, and Samaneh Heydari. "Wide band yagi antenna for terahertz application with graphene control." *Optik* 140 (2017): 866-872.

[23] Cheng, Ruijian, Ling Xu, Xin Yu, Liner Zou, Yun Shen, and Xiaohua Deng. "High-sensitivity biosensor for identification of protein based on terahertz Fano resonance metasurfaces." *Optics Communications* 473 (2020): 125850.

[24] Poorgholam-Khanjari, Shima, Zahra Razavi, and Ferdows B. Zarrabi. "Reconfigurable optical rectangular particle array absorber based on metal–DNA–metal structure as a refractive index sensor and optical switch." *Optics Communications* 489 (2021): 126866.

[25] Lue, Niyom, Gabriel Popescu, Takahiro Ikeda, Ramachandra R. Dasari, Kamran Badizadegan, and Michael S. Feld. "Live cell refractometry using microfluidic devices." *Optics letters* 31, no. 18 (2006): 2759-2761.

[26] Faustino, Vera, Susana O. Catarino, Rui Lima, and Graça Minas. "Biomedical microfluidic devices by using low-cost fabrication techniques: A review." *Journal of biomechanics* 49, no. 11 (2016): 2280-2292.

[27] Li, Xiangjun, Jian Song, and John XJ Zhang. "Design of terahertz metal-dielectric-metal waveguide with microfluidic sensing stub." *Optics Communications* 361 (2016): 130-137.

[28] Xing, Lei, Qian Xu, Jiajia Zhu, Yongjiu Zhao, Chaoyun Song, and Yi Huang. "A high-efficiency wideband frequency-reconfigurable water antenna with a liquid control system: usage for VHF and UHF applications." *IEEE Antennas and Propagation Magazine* (2019): 0-0.

[29] Fayad, H., and P. Record. "Broadband liquid antenna." *Electronics Letters* 42, no. 3 (2006): 133-134.

[30] Motovilova, Elizaveta, and Shao Ying Huang. "A review on reconfigurable liquid dielectric antennas." *Materials* 13, no. 8 (2020): 1863.

[31] Ren, Jian, Zhao Zhou, Zhao Hui Wei, Hao Ming Ren, Zhe Chen, Ying Liu, and Ying Zeng Yin. "Radiation pattern and polarization reconfigurable antenna using dielectric liquid." *IEEE Transactions on Antennas and Propagation* 68, no. 12 (2020): 8174-8179.

[32] Yomogida, Yoshiki, Yuki Sato, Ryusuke Nozaki, Tomobumi Mishina, and Jun'ichiro Nakahara. "Dielectric study of normal alcohols with THz time-domain spectroscopy." *Journal of Molecular Liquids* 154, no. 1 (2010): 31-35.

[33] Saha, Shimul C., James P. Grant, Yong Ma, A. Khalid, Feng Hong, and David RS Cumming. "Terahertz frequency domain spectroscopy for polar alcohol." In *2011 International Conference on Infrared, Millimeter, and Terahertz Waves*, pp. 1-2. IEEE, 2011.

[34] Arik, Enis, Hakan Altan, and Okan Esenturk. "Dielectric properties of ethanol and gasoline mixtures by terahertz spectroscopy and an effective method for determination of ethanol content of gasoline." *The Journal of Physical Chemistry A* 118, no. 17 (2014): 3081-3089.

[35] Jepsen, Peter Uhd, Jens Kristian Jensen, and Uffe Møller. "Characterization of aqueous alcohol solutions in bottles with THz reflection spectroscopy." *Optics express* 16, no. 13 (2008): 9318-9331.

[36] Liebe, Hans J., George A. Hufford, and Takeshi Manabe. "A model for the complex permittivity of water at frequencies below 1 THz." *International Journal of Infrared and Millimeter Waves* 12, no. 7 (1991): 659-675.

[37] Ellison, W. J. "Permittivity of pure water, at standard atmospheric pressure, over the frequency range 0–25 THz and the temperature range 0–100 C." *Journal of physical and chemical reference data* 36, no. 1 (2007): 1-18.

[38] Koeberg, Mattijs, Chien-Ching Wu, Doseok Kim, and Mischa Bonn. "THz dielectric relaxation of ionic liquid: water mixtures." *Chemical physics letters* 439, no. 1-3 (2007): 60-64.

[39] Poorgholam-Khanjari, Shima, Ahmad Hatami, and Ferdows B. Zarrabi. "Compact antenna based on split ring resonator as high Q-factor antenna for liquid permittivity measurements." *Frequenz* (2021).

[40] Møller, Uffe, David G. Cooke, Koichiro Tanaka, and Peter Uhd Jepsen. "Terahertz reflection spectroscopy of Debye relaxation in polar liquids." *JOSA B* 26, no. 9 (2009): A113-A125.