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Advanced Electromagnetic Metamaterials for Temperature Sensing Applications

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Metamaterials with novel properties have excited much research attention in the past several decades. Many applications have been proposed and developed for the reported metamaterials in various engineering areas. Specifically, for the resonant-type metamaterials with narrow resonance line width and strong resonance strength, the resonant frequency and strength are highly depended on the changings of meta-atom structure and/or substrate media properties induced by the environment physical or chemistry parameters varying. Therefore, physical or chemistry sensing applications for the resonant-type metamaterial units or arrays are developed in recent years. In this mini review, to help the researchers in those fields to catch up with the newly research advances, we would like to summarize the recently reported high-performance metamaterial-inspired sensing applications, especially the temperature sensing applications, based on different kinds of metamaterials. Importantly, by analyzing the advantages and disadvantages of several conventional metamaterial units, the newly proposed high quality-factor metamaterial units are discussed for high-precision sensing applications, in terms of the sensitivity and resolution. This mini review can guide researchers in the area of metamaterial-inspired sensors to find some new design routes for high-precision sensing.

Keywords: metamaterial, sensor, resonance, high quality factor, high precision sensing

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INTRODUCTION

Electromagnetic metamaterials are kinds of synthetic structural materials with novel electromagnetic properties not found in nature [1]. Researchers have found very wide applications for the electromagnetic metamaterials in the fields of electromagnetism, optics, and materials sciences [1–4]. Specifically, the resonant frequency and strength of resonant-type electromagnetic metamaterials are strongly correlated with unit cell structural parameters and dielectric material properties of substrates, and those structural parameters and/or dielectric properties can be tuned by changing the environment physical and/or chemistry parameters. Therefore, new sensing technologies based on the resonant-type electromagnetic metamaterials can be developed [5–9]. For examples, the electromagnetic metamaterials can be widely used to sense as well as detect the changes of media parameters, pressure, humidity, temperature, and chemistry/biology molecules in the environments [10–12]. Comparing with the conventional sensing techniques, the metamaterial-inspired sensing has the potential advantages including the high precision, label-free, safety, and can work properly in long-distance wireless situation. The explorations of sensing mechanism, sensing technology and device engineering based on the electromagnetic metamaterials are well-developed and its application methods in environmental sensing, chemical detection, biosensing and IoT emerging technologies are widely studied in recent years [13–18]. Previously reported review works have focused on the analysis of different sensing mechanisms, sensing methods, and wide application explorations [14–18]. However, the analysis on how to further improve the sensing performance is absent. Therefore, this mini review would like to summarize the recently reported high-precision sensing applications (especially the temperature sensing) based on the advanced high-performance resonant-type electromagnetic metamaterials.

RESEARCH PROGRESS

Overall Sensing Applications Analysis of Metamaterials

In the field of sensing applications based on the electromagnetic metamaterials, a variety of sensing technologies and design methods have been developed as mentioned above [5–13]. The sensing principle for most of the reported metamaterial-based sensors can be summarized as follows. At the resonant frequency of the electromagnetic metamaterial, a large number of electric field/magnetic field components are concentrated inside the basic unit of the electromagnetic metamaterial (meta-atom) and thus the macroscopic resonant frequency/strength characteristics of the electromagnetic metamaterial will follow the structural/material parameter changings inside the meta-atom. That means the characteristic changings of the dielectric material as well as the changes of surrounding environments will accordingly result in the changings of the resonant frequency or the resonant strength. Therefore, the external detection circuit and processing algorithm can be flexibly used to realize the changings monitoring of chemical/biological molecule types, gas concentrations, pressure, humidity and temperature. This sensing mechanism based on the metamaterials has many advantages compared to the conventional sensing techniques.

For examples, in the sensing fields of biology, chemistry, medicine, etc., traditional biosensors need to be labeled with fluorophores in the target. So the process is complicated, time consumed and expensive. Considering this problem, the researchers have developed different kinds of metamaterial-based sensors worked at optics [11, 12, 19], THz [20–26] and microwave [27–32], achieved groundbreaking realization methods and performances. Specifically, the refractive index of the medium around the meta-atom will be changed with the lesion level and chemical composition/concentration changings [33]. By detecting and analyzing the changes of the electromagnetic wave transmission/reflection amplitude at resonance or the resonant frequency caused by the corresponding refractive index changes, the lesion level and chemistry composition/concentration can be determined. In the field of hazardous gas or chemical sensing applications, researchers have also designed hydrogen concentration detectors based on nanorod-structured electromagnetic metamaterials [11] and hazardous chemical concentration detectors based on metal split ring resonator (SRR) [34]. When the used metamaterial is exposed to the hydrogen or there are different kinds and/or concentrations of hazardous chemical materials at the split of the metal SRR, the transmission/reflection characteristics (resonant frequency or strength) of the electromagnetic metamaterial will be changed. As a result, the hydrogen can be detected and analyzed accordingly and the concentration characteristics of other hazardous chemical materials can be detected as well.

In addition, the resonant frequency/strength characteristics of the electromagnetic metamaterial are not only strongly related to the properties of the dielectric material surrounding the meta-atom, but also depended on the distance between the meta-atom and the substrate dielectric material. The relative position changes of the dielectric material around the meta-atom will result in the changes of equivalent refractive index near the meta-atom. Accordingly, the researchers designed microwave and/or THz bands pressure sensor based on the electromagnetic metamaterials [33, 35]. In the field of humidity sensing applications, the humidity changes of the medium around the meta-atom can also cause the changes of equivalent refractive index of the medium [36]. Thereby, determining the humidity is achieved by detecting the resonant frequency/strength of the electromagnetic metamaterial. For example, Romero in [37] proposed a wireless capacitive sensing tag loaded with a metamaterial unit in a single-layer design. The selected metamaterial structure is the conventional SRR, which allowed the tag to be miniaturized and the sensor to be highly sensitive.

Metamaterial-Based Temperature Sensing Technology

Among the various metamaterial-based sensing applications, the temperature sensing is one of the key researches and application fields for the electromagnetic metamaterials. This is because some of the used substrate materials and/or constructed sub-wavelength structures have high temperature sensitive property. According to the sensing mechanism of resonant-type metamaterial-inspired sensors mentioned above, the temperature sensitive dielectric substrate materials and the sub-wavelength nano/micro mechanical structure with thermal expansion coefficient differences will result in the changings of resonant frequency/strength under different temperatures [38–42].

Temperature Sensing Based on Temperature-Sensitive Dielectric Inspired Metamaterials

Generally, for the electromagnetic metamaterials formed on the temperature-sensitive dielectric substrate, the resonant frequency/strength is highly related to the equivalent dielectric constant varying of such substrate induced by temperature changing. Various temperature-sensitivity dielectric substrates can be used, such as the low-temperature co-fired ceramic (LTCC) substrate, sea water, barium titanate, lithium niobate, etc. For examples, in 2010, Varadan and Ji pioneered the experimental studies for the resonant frequency/strength changing amounts of electromagnetic metamaterials based on the LTCC substrate due to the changings of the dielectric constant, electrical conductivity, and the thermal expansion of the medium during the temperature changes [43]. The results shown in this work indicated that the dielectric constant change has the main function (accounting for 84.03%).

In 2012, Ekmekci and Turhan-Sayan explored the temperature-sensing characteristics of SRR filling with sea water as the background medium [44]. For the proposed miniaturized metamaterial sensor prototype operating at X-band, a 158-MHz resonant frequency shift corresponds to a 20°C temperature change is achieved, leading to an average sensitivity level of 7.9 MHz/°C. In 2014, Zhang et al. used barium titanate (Ba0.5Sr0.5TiO3, BST) as a temperature-sensitive medium of the dielectric-type metamaterial and analyzed the temperature sensing mechanism [45]. An electric resonance characteristic with Lorentz-type dispersion of effective permittivity is seen around the resonant frequency. The relative permittivity of dielectric cut-wire is decreased with the increase in environmental temperature, hence, resulted in the blue shift of electric resonant frequency, with a calculated temperature sensitivity of 25 MHz/°C. In 2015, Karim et al. designed a closed-ring resonator (CRR) and a variety of open-ring resonators based on lithium niobate (LiNbO3) and compared their respective temperature sensitivity performances [46, 47]. This CRR structure-based sensor has a sensitivity up to 7.286 MHz/°C. At the same year, Zemouli et al. proposed a metamaterial sensor consisting of two concentric metallic rings and a thin metallic wire deposited on the surface of $BaTiO_3$ substrate and studied the variations of the resonant frequency according to the permittivity changing under varied temperatures [40].

In 2017, Karim et al. further designed an array of CRRs embedded in a multi-layer dielectric substrate [48]. A mixture of 70 vol% Boron Nitride (BN) and 30 vol% Barium Titanate (BTO) was used as the dielectric substrate. It was observed that for a temperature change from 23 to 200°C, the change in resonant frequency is 81.75 MHz, corresponding to a temperature sensitivity of 0.462 MHz/°C. At the same year, Qiu and Liu presented a thermally tunable Fano resonator obtained by asymmetrically coupling a conductive rubber-based H-shaped split ring resonator (SRR) and a copper C-shaped SRR coated on a Teflon fiberglass slab substrate [49]. At the Fano resonance, surface current distributions are anti-symmetric since the current excited in the H-shaped conductive rubber-based SRR and the C-shaped copper SRR are opposite and almost equal in magnitude. Consequently, the electrical and magnetic fields are canceled out, resulting in a high quality factor. Therefore, with the increase in temperature, the Fano resonant frequency was slightly shifted from 11 to 10.5 GHz, and the transmission loss gradually increased as well. For more details about the high quality factor metamaterials used in the high-performance temperature sensing area will be discussed in later.

In general, the temperature-sensing technology based on temperature-sensitive dielectric substrates has the advantages of miniaturization, high flexibility and simple preparation process. However, its dielectric constant changes with temperature increase/decrease are in a very limited linear range. The inherent drawbacks such as low sensitivity and small dynamic range of this kind of metamaterial-based sensors will be limited for the practical application.

Temperature Sensing Based on the Thermal Expansion Coefficient Difference

Based the different thermal expansion coefficients of different substrates used in the metamaterials, the bending deformations due to the changes of background temperature will alter the equivalent capacitance/inductance parameters of the meta-atom, thereby causing the resonant frequency shift or resonance strength change. For examples, Thai et al. firstly loaded a cantilever arm at the open slot of the metal SRR as shown in **Figure 1A-i** [38, 50]. The arm consisted of two layers of heterogeneous materials with different thermal expansion coefficients. The upper layer was silicon with a smaller thermal expansion coefficient while the lower layer and the arm are all aluminum with larger thermal expansion coefficient. When the temperature is changed the cantilever will bend upwards or downwards, as a result affecting the equivalent capacitance value of the metal SRR. **Figures 1A-ii,iii** show the experimental transmission curve changes with different background temperatures, and a frequency shift of 800 MHz from 4.8 to 4.0 GHz can be seen.

Moreover, based the well-developed nano-fabrication process, temperature sensing and detection can be realized in the THz and optical frequency bands by constructing nano-scale MEMS metamaterial structures. For examples, in 2011, Ou et al. designed the nanoscale reconfigurable photonic metamaterials and the structure is shown in **Figure 1B-i** [51]. The Au-Si3N4-Au sandwich symmetrical structure shown in this figure has a very small deformation due to temperature change, while the two-layer structure composed of metal-semiconductor (Au-Si3N4) can show obviously deformation. The resonant properties of this system utterly depend on the coupling between neighboring bridges. For example, from **Figure 1B-ii** it can be seen that as the background temperature is increased, a dramatic increase of its transmission amplitude near its resonant frequency is achieved. Importantly, as the metamaterial structure was cooled back to its initial temperature these changes of its transmission spectrum were reversed.

In addition, Alves et al. constructed a MEMS temperature-sensing micro-mechanical arm on a semiconductor body and explored the temperature sensing technique in the terahertz band [29]. The sensor's absorbing element is designed with a resonant frequency that matches the source of the quantum cascade laser illumination. At the same time the semiconductor layer provides structural support, desired thermomechanical properties. As shown in **Figure 1C-i**, the absorbing element is connected to two Al/SiOx microcantilevers (legs), anchored to a silicon substrate, which acts as a heat sink, allowed the sensor to return to its undisturbed position when the excitation was stopped. **Figure 1C-ii** shows the experimental results for the temperature sensing properties, which indicates a sensitivity of 0.2 deg/°C.

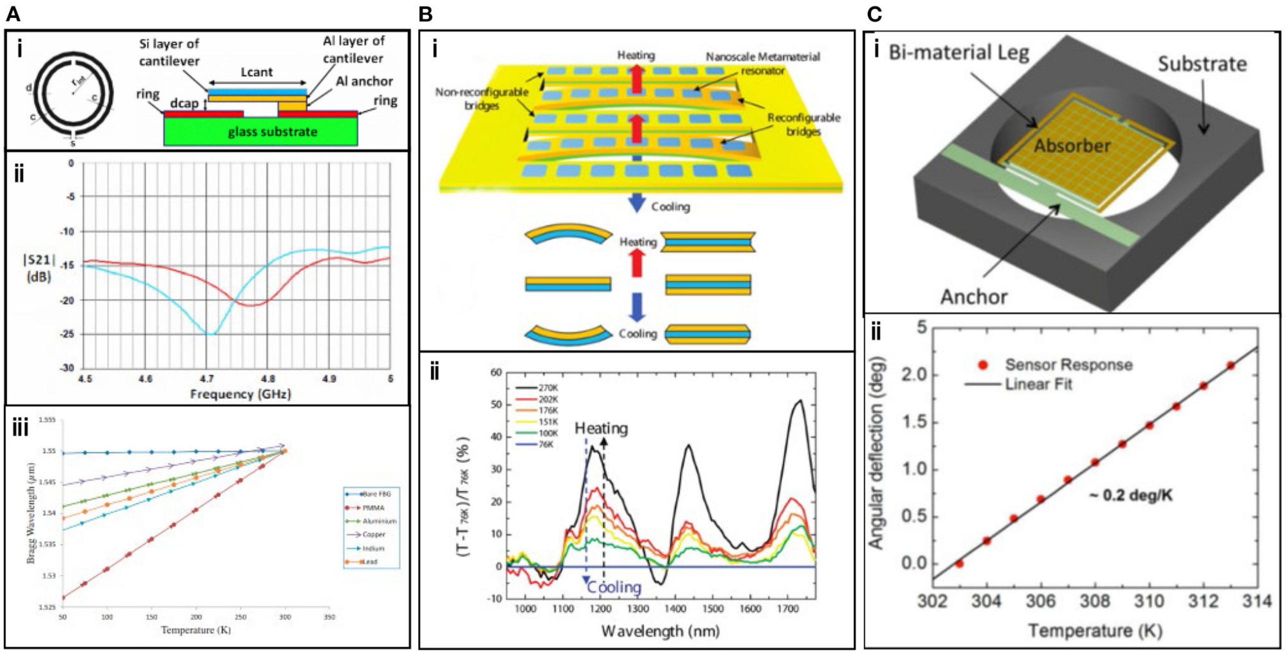

FIGURE 1 | Temperature sensitivity metamaterial units. **(A)** SRR on a cantilever arm, and the transmission spectra and resonant frequency response under different temperatures [38, 50], **(B)** nanoscale reconfigurable photonic metamaterials and the corresponding temperature changing performances [51], **(C)** Metamaterial absorber configuration fabricated on a microcantilevers and the accordingly temperature changing inspired structure deformation performance [29].

Generally speaking, the temperature sensing based on the difference in thermal expansion coefficient, especially for nanoscale MEMS micro-mechanical structure, mainly worked in the optical and THz frequency bands and had the advantages of reconfigurability, miniaturization and easy to integration. However, the shape deformation due to the difference in thermal expansion coefficient of heterogeneous composites is weak. And it also has complicated preparation process, high processing difficulty and high cost.

Sensitivity Enhancement Design of Electromagnetic Metamaterial Based Sensor

The above research progresses and results demonstrated the feasibility of electromagnetic metamaterials in the field of sensing application. However, the researchers did not thoroughly study the specific technical methods to optimize and improve the sensitivity and resolution of sensing. According to the resonance type sensing theory, high sensing sensitivity and resolution require the sensing unit's resonance quality factor and the FOM (FOM is defined as the ratio of the sensitivity to the resonance 3-dB bandwidth) to be as high as possible [52, 53]. A resonant-type sensor based on the meta-atom the has a large amount of electric field/magnetic field components accumulated inside the resonance unit (e.g., at the opening gap of the SRR) during resonance. Therefore, it is an effective way to further improve the sensitivity and resolution of the resonant-type sensors by enhancing the electric field/magnetic field components of the electromagnetic metamaterial while effectively reducing the loss, to increase the resonant quality factor and improve the FOM of the sensor devices.

Based on the above suggestions, researchers have explored a variety of technical methods to improve the sensitivity of sensor, starting from the study of the resonance characteristics of new electromagnetic metamaterials. Firstly, the planar absorber composed of electromagnetic metamaterial can be equivalent to a Fabry-Perot cavity. The electric and magnetic field energy during resonance is well-bounded inside the cavity, and the radiation loss is small, resulting in the high resonant quality factor. Thus, the metamaterial absorbers can be used to improve sensing sensitivity and resolution for sensing application. For example, Cong et al. and Yahiaoui et al. studied the THz band single-frequency and multi-frequency metamaterial absorber based high-sensitivity sensors [25, 26], as shown in **Figure 2A-i**. It was observed from this figure that the FOM value of metamaterial absorber sensors have been found to be significantly higher than those of planar metamaterial resonators. The measured frequency shift of the sensors for different analyte thicknesses is shown in **Figure 2A-ii**. It was analyzed that the total frequency shift saturated at about 14.0%.

Moreover, Dong et al. achieved an electromagnetic-induced transparency (EIT) resonance characteristics based on the interaction between different electromagnetic metamaterial units and incident electromagnetic waves [54]. They used the three-bar

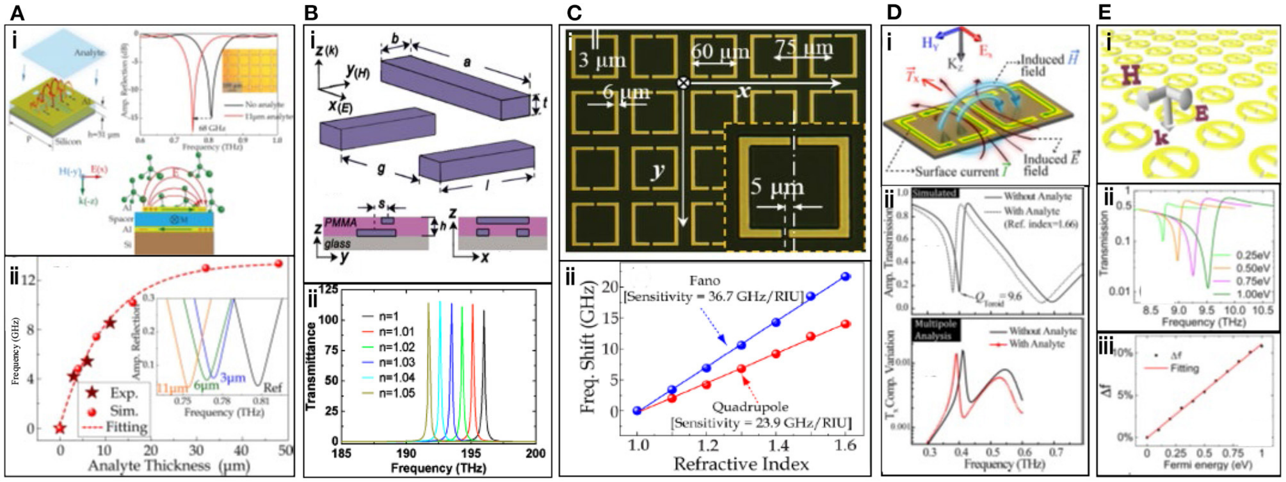

FIGURE 2 | Performance enhanced metamaterial unit based sensors. **(A)** CSA and CCSA based Fabry-Perot cavity type sensors and the sensing performance [25, 26], **(B)** schematic illustration of EIT-like metamaterial unit and the enhanced narrow transparency windows at different refraction indexes [54], **(C)** microscopic image of the terahertz asymmetric Fano resonances shift with the change in refractive indexes [24], **(D)** operating mechanism for the toroidal resonance and the corresponding resonance changing performance [55], and **(E)** schematic illustration for the newly developed graphene-inspired anapole resonator and the accordingly resonance changings under different Femi levels [56].

configuration to investigate the active plasmon analog of the EIT in order to improve the performance of the refractive-index fluctuation sensing of the surrounding medium which can be seen in **Figure 2B-i**. The result shown in this work (e.g., **Figure 2B-ii**) is higher than the traditional metamaterial resonance unit, which can be used to improve sensing sensitivity and resolution.

On another hand, Singh et al. broke the basic electromagnetic metamaterial unit structure and proposed a new Fano asymmetric resonance which can be seen in **Figure 2C-i** [24]. From that method they were able to achieve sensitivity levels of 7.75×10^3 nm/refractive index unit (RIU) for quadrupole and 5.7×10^4 nm/RIU with the Fano resonance. The sensitivity of Fano resonance gets enhanced due to much stronger interaction of analyte layer with the enhanced electric field in the capacitive gaps as shown in **Figure 2C-ii**. Semouchkina et al. also applied a full-scale electromagnetic metamaterial in a parallel version of the metal waveguide to achieve an ultra-high-Q Fano resonance characteristic, and explored the design method of a high-sensitivity sensor [57]. In addition, in 2016, Campione et al. presented a new approach that relies on a single resonator and produces robust, high quality-factor Fano resonance, by breaking the highly symmetric resonator geometries, such as cubes, to induce couplings between the orthogonal resonance modes. In particular, they designed perturbations that couple "bright" dipole modes to "dark" dipole modes whose radiative decay is suppressed by local field effects, achieving a quality-factor of $\sim$600 [58].

For those proposed high quality-factor metamaterials, it can be used very easily in the high-precision temperature sensing area if those meta-atoms are designed on the temperature sensitivity substrates or the meta-atom is composed directly by the temperature sensitivity metals.

DISCUSSION AND PERSPECTIVE

Based on the performance enhanced sensing designs by using the asymmetric high quality-factor resonance mode, in the past several years, researchers further proposed other kinds of high quality-factor metamaterial units for sensing applications, including the toroidal resonance [55, 59–61], anapole resonance [56, 62–67], and enhanced magnetic plasmon resonance [68–74]. For examples, by placing the period symmetric arrangement of the Fano resonator shown in **Figure 2C-i** as the mirror symmetric arrangement shown in **Figure 2D**, one can get the toroidal resonance with quality factor larger than the regular Lorentz resonance [63]. By concentrating the electric and magnetic field within the resonator of the new kind of anapole resonator shown in **Figure 2E**, the sensing resolution can be further enhanced as anticipated [67].

CONCLUSION

In summary, the sensing based on the electromagnetic metamaterials has developed rapidly in terms of sensing mechanism and implementation methods. Especially in the field of temperature sensing area, a variety of resonant-type temperature sensing technologies and many achievements have emerged in the past years, and researches and explorations have been carried out for further optimization and improvement of sensing sensitivity and resolution. Most of the existing temperature-sensing technologies based on temperature-sensitive dielectric materials, thermal expansion coefficient difference, and nano-scale MEMS structure are all derived from the dielectric constant, material shape, mechanical structure, etc. The sensing sensitivity improvement technologies based on high-quality-factor electromagnetic metamaterials are explored.

AUTHOR CONTRIBUTIONS

LM, DC, WZ, JL, and YH discussed together and proposed the review paper content. LM, SZ, YH, and GW modified the review paper frame. DC, YL, and YZ finished the references collection and figure preparation. LM and DC finished the whole manuscript writing. JL, YH, and GW finished the whole manuscript modification and finalization. All authors finished the proofread.

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Conflict of Interest: WZ was employed by company Shenzhen Intellifusion Technologies Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.