Terahertz Sensor Using Photonic Crystal Cavity and Resonant Tunneling Diodes

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Abstract In this paper, we report on a terahertz (THz) sensing system. Compared to previously reported systems, it has increased system sensitivity and reduced size. Both are achieved by using a photonic crystal (PC) cavity as a resonator and compact resonant tunneling diodes (RTDs) as signal source and as detector. The measured quality factor of the PC cavity is higher than 10,000, and its resonant frequency is 318 GHz. To demonstrate the operation of the refractive index sensing system, dielectric tapes of various thicknesses are attached to the PC cavity and the change in the resonator’s refractive index is measured. The figure of merit of refractive index sensing using the developed system is one order higher than that of previous studies, which used metallic metamaterial resonators. The frequency of the RTD-based source can be swept from 316 to 321 GHz by varying the RTD direct current voltage. This effect is used to realize a compact frequency tunable signal source. Measurements using a commercial signal source and detector are carried out to verify the accuracy of the data obtained using RTDs as a signal source and as a detector.

Keywords Photonic crystal · Cavity · Resonant tunneling diode · Terahertz · Sensing

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1 Introduction

Terahertz (THz) waves are located between radio waves and light waves (100 GHz to 10 THz) in the electromagnetic spectrum. Therefore, like radio waves they can penetrate materials, and like light waves they have a high directionality. Unique potential applications of THz waves, such as spectroscopic sensing, nondestructive imaging, and broadband communications, have been developed [1–3]. Especially, sensing applications are attracting much attention in the fields of biology, medicine, chemistry, physics, environment monitoring, and material science [4–6].

Improving the sensitivity and reduction of the system size will result in the development of new applications. The use of a resonator can improve the sensitivity [7]. In refractive index sensing, the change in resonant frequency due to a specimen being added to the resonator is measured. This can be used to examine and identify samples with a high sensitivity. THz sensing using metamaterial metallic resonators has been widely studied for high-sensitivity applications [8–11]. However, the minimum detectable refractive index change $\Delta n$ [7], which is important for practical, highly sensitive microanalysis, is limited by the low $Q$ factors of the metamaterial metallic resonators (approximately 10–70) due to ohmic loss. In the light wave region, high sensitivities have been reported using a high $Q$ factor photonic crystal (PC) cavity [12–17]. A PC is composed of dielectric materials with a periodic refractive index distribution. In the THz region, PC slabs [18–34] and their applications such as planar low-loss waveguide have been demonstrated [32]. High-$Q$ THz PC micro-cavities (approximately 1000–9000) [25, 29, 30, 34] and their applications in sensing have been recently reported [30, 34].

Time-domain spectroscopy (TDS) [35, 36] and frequency-domain spectroscopy (FDS) [37–39] based on the laser system are widely used. However, these systems require a large THz source and bulky free-space optical components such as mirrors and lenses. If these cumbersome systems can be integrated into planar circuits, THz sensing modules with a handy size can be realized. So far, sensing devices based on metallic circuits and external pulse laser sources have been studied for a compact sensing system [4, 40–43]. However, the loss of metal restricts the system performance, and an external source is still required.

We aim to use resonant tunneling diodes (RTDs) with semiconductor quantum structures as a compact THz source and as a detector integrated with the PC waveguide and cavity. The RTD oscillator can generate a coherent THz wave at room temperature [44–55], and an oscillation frequency of approximately 2 THz has been reported [50, 54]. The oscillation frequency can be changed by voltage [45, 46, 51, 53–55] and can be applied to THz sensing systems [34]. Highly sensitive RTD detectors have been realized exploiting the strong nonlinearity of the RTD’s current–voltage characteristics [48, 49, 53, 55].

Previously, we have reported on the integration of RTDs with a PC slab for THz communication [3, 28, 31]. Here, we propose a compact-integrated THz sensing module based on a PC slab and RTDs as shown in Fig. 1. An RTD oscillator and a detector are integrated at the input and output ports of a PC waveguide, respectively, which is coupled to a cavity. Application specific integrated circuits (ASICs) can be used for driving the RTDs and analyzing the data signal. The resonant spectrum of the PC cavity is measured by detecting the output signal when the input frequency is swept.

In this paper, we demonstrate a PC cavity with a $Q$ factor $> 10,000$ and report on the results of a sensing test using thin dielectric tapes as the specimen. In Sect. 2, we introduce a PC system comprised of a PC cavity coupled to a PC waveguide. Its properties are characterized using a commercially available signal source and detector. In Sect. 3, we carry out refractive
index sensing using the system as described in Sect. 2 and compare it with the state-of-the-art of metamaterial-based sensing systems. In Sect. 4, we replace the commercial signal source and detector with RTDs to realize a compact THz sensing system. The data obtained with the two systems are compared to verify the accuracy of the compact RTD-based sensing system. We conclude our results and present the future perspective in Sect. 5.

2 PC Cavity Structure and Property

We employed a two-dimensional triangular lattice of air holes in a Si slab as a PC to achieve a broadband photonic band gap (PBG) effect [56]. The PC waveguide is formed as a line defect, and the THz wave is confined in both the vertical and in-plane directions by total internal reflection and the PBG effect, respectively. A low propagation loss is achieved using high resistivity Si [32]. We used the waveguide as the input-output interface of the PC cavity, as shown in Fig. 2, and only the resonant

![Fig. 1 Schematic image of THz sensing module based on PC slab and RTD](image)

![Fig. 2 Schematic of PC cavity. (a) PC cavity consists of three missing air holes. $a$ and $r$ denote lattice constant and hole radius of PC. (b) Integration with input-output waveguide. $W$ is a number of rows between cavity and waveguide](image)
frequency is coupled from the waveguide to the PC cavity [57]. The coupling strength is influenced by the number of rows $W$ between the waveguide and the cavity. The PC cavity consists of three missing air holes, and the position of the holes located at both the edges of the cavity is shifted by $0.15a$ to the outside [58], where $a$ is the lattice constant of the PC. The values of $a$, the radius of the air hole $r$, and the thickness of Si were set to 240, 72, and 200 $\mu$m, respectively.

Figure 3 shows the system used to measure the resonant spectrum. The multiplier system (height 9 cm × width 13 cm × length 21 cm, Virginia Diodes, Inc.) was used as the frequency tunable THz source. The input frequency was swept from 317 to 319 GHz. The output signal from the waveguide was down-converted to an intermediate frequency (IF) signal by mixing with a local oscillator (LO) signal generated by a spectrum analyzer connected to an external mixer (height 9 cm × width 13 cm × length 21 cm, Virginia Diodes, Inc.). The ends of the waveguides are terminated by a tapered structure [32]. The tapered structures of port 1 and port 3 were inserted into a WR-3 rectangular waveguide with a low insertion loss (<0.2 dB). The tapered structures of port 2 and port 4 suppressed the reflection at the end of waveguides. Figure 4 shows the measured spectrum. The resonant frequency $f_r$ and linewidth (the full-width at half-maximum) $\Delta f$ are 318.056 GHz and 28 MHz, respectively. The $Q$ factor is estimated using $f_r/\Delta f$ to be 10,800. Figure 5 shows the $Q$ factor for various rows $W$. The $Q$ factor increases with $W$ due to the reduced coupling between the cavity and the waveguide [59].

![Fig. 3](image)

**Fig. 3** Block diagram of the PC cavity measurement system using multiplier and mixer. The output from the waveguide was down-converted to an IF signal by mixing with LO signals that were generated by the spectrum analyzer.

![Fig. 4](image)

**Fig. 4** Measured resonant spectrum of the PC cavity ($W = 6$)
3 Sensing Test Using PC Cavity

The sensitivity of the cavity’s refractive index change can be defined as $S = \delta f / \delta n$ where $\delta f$ is the shift of the resonant frequency resulting from the refractive index change $\delta n$ due to the specimen. The normalized sensitivity of $S' = S / f_r$ is used to make a comparison among different cavity systems [7]. The minimum detectable refractive index change $\Delta n$ which depends on the cavity linewidth or $Q$ factor is important for practical applications, and it can be expressed as $(S' Q)^{-1} [7]$. A smaller $\Delta n$ corresponds to a higher sensing resolution or effective sensitivity; therefore, $1/\Delta n$ can be considered as the figure of merit (FOM) for sensing the refractive index using a cavity.

THz sensing experiments were performed by sticking dielectric polyester tapes (refractive index $n_{tape} \sim 1.6$) of different thicknesses $T_{tape}$ (5, 10, 30 μm) on the PC cavity, as shown in Fig. 6. The resonant frequency of the cavity changes with its effective refractive index, i.e., it changes with the tape thickness. Figure 7a shows the experimental resonant spectra for different tape thicknesses. The resonant frequency peak was red-shifted as the thickness of tape increased, as shown in Fig. 7b. The experimental plots were consistent with the simulated curves. In Fig. 8, a comparison of the FOM ($=1/\Delta n$) of the present study with that of metamaterials reported in [8–11] and the metallic circuit resonator [40] is presented as a function of the $Q$ factor. Figure 8 demonstrates that the FOM of the PC cavity is one order higher than that of metamaterials owing to its high $Q$ factor although $S'$ is approximately

![Simulated vs Experimental Q factors](image-url)
0.002. If $S'$ can be increased in a PC cavity while maintaining a high $Q$ factor, e.g., by using a slot cavity [60], the FOM can be further improved.

Fig. 7 Sensing test results. (a) Spectra for various tape thicknesses $T_{\text{tape}}$. Blue, green, yellow, and red curves denote for $T_{\text{tape}} = 0, 5, 10, \text{and } 30 \mu m$, respectively. (b) Shift of resonant frequency peak versus tape thickness $T_{\text{tape}}$. Solid plots and dotted line denote that for experiment and simulation, respectively.

Fig. 8 FOM of refractive index sensing using various resonators as a function of cavity $Q$ factor. Circle, diamonds, and square represent the PC cavity, metamaterials [8–11], and metallic circuit resonator [40], respectively.
4 Employment of RTD Source and Detector Integrated with PC

An RTD structure was grown on a semi-insulating InP substrate. A GaInAs/AlAs double barrier quantum well-constituted the tunneling region. The layer structure of the RTD was similar to that shown in [53]. We used an RTD integrated with a dipole antenna and a resonator circuit [49]. The capacitance and inductance of the circuit were approximately 10 fF and 20 pH, respectively, and the resonant frequency was approximately 300 GHz. Figure 9 shows the current–voltage curve of an RTD with an electrode mesa area of 1.9 μm². Oscillation occurred in the region of negative differential resistance (NDR) owing to the gain of the circuit. The oscillation frequency with a spectral linewidth of ~7 MHz can be tuned by varying the RTD direct current (DC) voltage, which is due to the voltage-dependent capacitance of the RTD [53]. Figure 10 shows the voltage dependence of the oscillation frequency measured by a mixer and a spectrum analyzer. The RTD source mounted on a 5.6 mm-can package was inserted into a WR-3 rectangular waveguide horn antenna to act as a signal source in the spectroscopic sensing system, as shown in Fig. 11. The coupling efficiency between the RTD and the waveguide was approximately 0.1%. The oscillation frequency increased monotonically from 316 to 321 GHz as the applied voltage was changed from 0.55 to 0.60 V. The RTD
was used as a frequency tunable source to replace the commercial signal source of the previously shown experiment set-up.

Furthermore, the RTD can be used as a square-law detector if the voltage is set in the region outside the NDR [48, 49, 53, 55]. We integrated a RTD-based detector with a PC cavity as shown in Fig. 11. The RTD chip was mounted on the PC waveguide of port 3, and the RTD was aligned with the center of the PC waveguide [31]. The THz wave propagating in the PC waveguide was evanescently coupled to the RTD chip, and it excited the dipole antenna with the coupling efficiency < 0.1%. The coupling efficiency was low because the RTD chip was

![Diagram](image_url)

**Fig. 11** Photograph of THz system using RTD source and RTD detector integrated with PC sample

![Diagram](image_url)

**Fig. 12** Block diagram of THz system using RTD detector integrated with PC. (a) RTD as the THz source. (b) Multiplier as the THz source
not optimized for this application. It will be improved in the future as it limits the performance of the present system. The THz wave is detected by the RTD, and the detected baseband signal is routed to a coaxial connector via an Au bonding wire and a coplanar waveguide.

The THz wave from the RTD was coupled into the PC waveguide of port 1 via a tapered structure as shown in Fig. 12a. A DC and alternative current (AC) signal were applied to the RTD through a bias-tee. Figure 13 explains the modulation scheme. The DC signal causes the RTD to oscillate, while the AC signal modulates the oscillation by turning it on-off. The frequency and amplitude of the modulation signal were set to 1 MHz and 0.5 V peak-to-peak, respectively. The oscillation frequency of the RTD-based oscillator was tuned by sweeping the applied DC voltage in steps of 0.1 mV. The signal coupled through the cavity was detected by the RTD at port 3, and the signal strength was measured by a spectrum analyzer at 1 MHz. In order to obtain the power adjacent at the input of the RTD detector, the square-root of the 1 MHz spectrum analyzer signal has to be taken. This is because the RTD acts as a square-law detector [48, 49, 53, 55].

Figure 14 shows the power at the input of the RTD detector versus frequency and compares it to the measured signal power using the commercial multiplier source. It can be seen that the shape of the two curves is very similar. The frequency of the peak is at 317.78 and 317.76 GHz for the system using a commercial and RTD-based source, respectively. The slight frequency shift of the measured spectrum could be due to the external feedback effect of RTD output [61, 62].

Fig. 13 Schematic explanation of the RTD source modulation for measurement using RTD detector

Fig. 14 Resonant spectrum of PC cavity using RTD detector. Plots and line denote that using multiplier and RTD as source
reflected by the PC cavity. This indicates that the coupling between RTD oscillator and PC cavity should be carefully designed. It can be seen that the data obtained using the RTD shows a relatively high fluctuation versus frequency. This is in part due to the reduced signal-to-noise ratio because of the low-efficiency coupling of the RTD detector and in part due to error-multiplication due to the normalization of the data. Future systems with increased RTD circuit coupling efficiency aim to overcome this problem.

5 Conclusion

We reported on a high-$Q$ (>10,000) THz PC cavity in a planar waveguide system to realize a highly sensitive, compact sensing system. Compared to previously reported systems using metamaterials, the FOM achieved here was one order higher demonstrating the advantage of PC-based sensing systems. We successfully measured the resonant spectrum of a PC cavity integrated with an RTD detector and an RTD source module. This demonstrated the feasibility to use an RTD oscillator as a tunable source for sensing. The sensitivity of the developed system can be further increased by improving the coupling efficiency of the RTD circuits to the PC waveguide, i.e., by increasing the system’s signal-to-noise ratio. The higher cavity $Q$ can enhance the FOM, and reduction in RTD oscillator spectral linewidth [63] is required. Integration of an RTD mixer [52] will enable the system to directly measure the source frequency. Our results reveal new possibilities in the field of compact THz sensing systems. Frequency multiplexing of the resonant frequency using a photonic heterostructure [64] and increasing the operating frequency over 1 THz will further extend the sensing applications.

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