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Purcell Effect of THz Emission using Multilayer Photonic Micro-Structures

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Abstract

We studied the enhancement of THz emission by the Purcell effect using multilayer photonic micro-structures such as microcavity type one-dimensional photonic crystals and hyperbolic metamaterials.

1. Introduction

Spontaneous emission rate of atoms or excitons can be enhanced if optical density of state (ODOSs) around them is modified by microcavity or photonic crystal. This phenomenon is well-known as Purcell effect [1]. There have been many experimental investigations on the enhancement of spontaneous emission in various material systems. Moreover, Purcell effect of other optical phenomena such as thermal radiation, Raman scattering and nonlinear optical effects has been investigated. We also have investigated the enhancement of THz emission by optical rectification using one-dimensional photonic crystal (1D-PC) [2,3].

On the other hand, enhancement of the spontaneous emission has been achieved using metal-dielectric multilayer metamaterials [4]. In this system, since the dispersion relation curve is hyperbolic instead of circular or elliptic as in usual dielectrics, the ODOS is greatly enhanced in wide spectral region. A transition probabilities of any optical processes are dependent on the ODOS derived by the time-dependent perturbation theory. Thus, the Purcell effects of various optical phenomena can occur owing to the modification of the ODOS using not only the microcavity or photonic crystal, but also hyperbolic metamaterials.

In this paper, we studied the enhancement of THz emission by the Purcell effect using multilayer photonic micro-structures such as microcavity type 1D-PCs and hyperbolic metamaterials.

2. One-dimensional photonic crystals

In this study, the 1D-PC cavity consists of two plane mirors made of multilayer dielectrics. We fabricated THz 1D-PC microcavities consisting of a semiconductor for THz generation by simple stacking method. The schematics of 1D-PC microcavity sample are shown in Fig. 1(a). Here, we used 46 μm-thick SiO_2 substrates with a refractive index of 2.12 and 100 μm-thick air spacers as a high and low index materials, respectively. We applied anti-reflection multilayer coatings for visible excitation light on the SiO_2 layer to avoid reduction in the excitation light intensity owing to Fresnel reflection at the interfaces between the SiO_2 and air layers. The GaP crystal, whose refractive index and thickness are 3.32 and 380 μm, respectively, was placed at the center of the structure as the cavity layer.

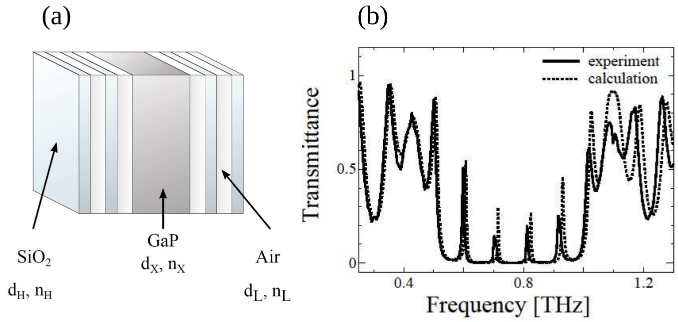

Fig. 1 Schematic of THz region 1D-PC microcavity (a) and its transmission spectrum (b).

The transmission spectra of the samples were measured via THz time-domain spectroscopy (THz-TDS). In our experimental system, an InAs substrate was excited by ultrashort pulses from a mode-locked Ti: sapphire laser to generate THz waves. The center wavelength, time duration, and repetition rate were 800 nm, 50 fs, and 76 MHz, respectively. THz detection was performed by means of an EO sampling method using a ZnTe crystal. The lock-in detection of the signal was carried out using intensity-modulated excitation pulses at 3 kHz. The THz wave was focused onto the sample by an off-axis parabolic mirror with a spot-size of 1 mm. The average power of the laser pulse incident on InAs was 2.7 nJ.

The transmission spectrum of 1D-PC is shown in Fig. 1(b). The solid lines represent the experimentally obtained spectrum and the dashed lines represent the theoretical calculation obtained by the transfer matrix method. In the calculation, the extinction coefficient of the GaP was taken into account. The center frequency of the photonic bandgap was 0.78 THz, and four peaks of the resonant modes appear in the photonic bandgap between 0.5 THz and 1 THz. The experimental results and calculations show good agreement.

In such structures, it is expected that modifications in the THz emission spectra occur owing to the difference in the ODOS from that of vacuum. We performed the THz emission experiments using the 1D-PC microcavity via THz-TDS. The experimental procedure to achieve emission was almost identical to that mentioned in transmission measurement. Here, a 1D-PC microcavity with a GaP crystal was used as a THz emitter instead of the InAs substrate. THz waves were generated using the optical rectification effect of the GaP crystal in a 1D-PC microcavity. A THz emission experiment using a bare GaP crystal as a THz emitter was also performed via THz-TDS for comparison.

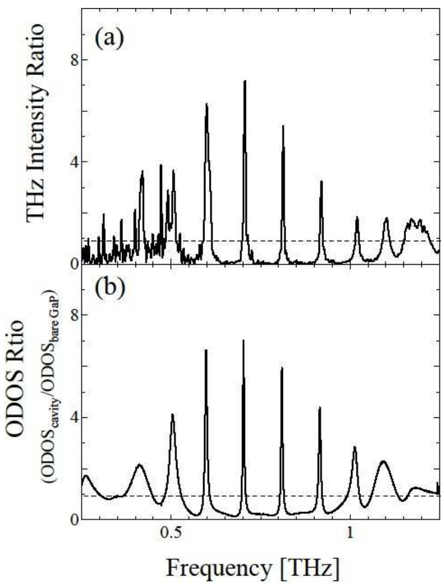

Fig. 2 (a) THz intensity ratio of the experimentally obtained emission spectra, (b) ODOS ratio obtained by transfer matrix calculation. [3]

Figure 2(a) shows the THz intensity ratio of the experimentally obtained emission spectra from the 1D-PC microcavity and that from the bare GaP crystal. An intensity ratio larger than unity indicates enhancement of THz emission. The intensity ratio spectrum appears to be closely related to the transmission spectrum shown in Fig. 1(b). The frequency regions where the intensity ratio is almost zero are located at the same regions of the photonic bandgaps. This indicates that THz emission is suppressed at the photonic bandgaps. On the other hand, THz emission from the 1D-PC microcavity is enhanced in the resonant mode and the photonic band edge; enhancement by a factor of 7 is observed at 0.7 THz [3].

Figure 2(b) shows the ODOS ratio between the 1D-PC microcavity and the bare crystal as obtained by transfer matrix calculations. In the calculation, we accounted for the extinction coefficient of the GaP crystal. The spectra shapes of the experimentally obtained THz intensity ratio and the ODOS ratio exhibited a close agreement.

3. Hyperbolic metamaterials

The multilayer structures composed of the two kinds of materials whose sign of dielectric constant are negative (metals) and positive (dielectrics) show hyperbolic type of dispersion relation. This system is called as hyperbolic metamaterial. Since the hyperbolic dispersion relation is not closed shape, there are many states that can be emitted the photon from the light source in the structure. Based on the advantages, the enhancement of the spontaneous emission of dye molecule or quantum dots has been reported. The mechanism of the enhancement in hyperbolic metamaterial is different from the Purcell effect in microcavity. Although in microcavity, the enhancement is occurred only at the resonant frequency, in metamaterial, broadband enhancement in emission spectrum is possible. We applied to the optical rectification for THz emission of this broadband Purcell effect.

In order to realize the hyperbolic dispersion in THz region, we utilize metal wire structure as the negative dielectric constant material. The plasma frequency of the usual metal located at ultraviolet region, and below the plasma frequency, metal has a negative dielectric constant. However, the absolute value of the dielectric constant become order of 100000 in the THz region, and this value is too large to realize the hyperbolic dispersion with normal dielectric materials with positive dielectric constant whose absolute value of dielectric constant is order of 10 to 100. We plan to fabricate the multilayer structure composed of semiconductor substrates as the positive dielectric material and metal wire structures as the negative dielectric material as shown in Fig. 3. The details are under investigation.

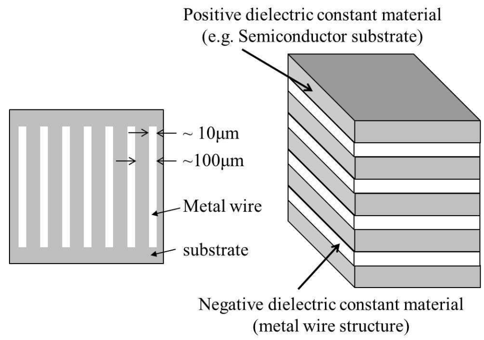

Fig. 3 Schematic of THz region hyperbolic metamaterial

4. Conclusion

We studied the enhancement of THz emission by the Purcell effect using multilayer photonic micro-structures such as microcavity type 1D-PCs and hyperbolic metamaterials. By microcavity type 1D-PCs, we observed 7 times enhancement of THz emission.

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