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A low threshold nanocavity in a two-dimensional 12-fold photonic quasicrystal

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ABSTRACT

In this article, a low threshold nanocavity is built and investigated in a two-dimensional 12-fold holographic photonic quasicrystal (PQC). The cavity is formed by using the method of multi-beam common-path interference. By finely adjusting the structure parameters of the cavity, the Q factor and the mode volume are optimized, which are two keys to low-threshold on the basis of Purcell effect. Finally, an optimal cavity is obtained with Q value of 6023 and mode volume of 1.24×10^{-12} cm^3. On the other hand, by Fourier Transformation of the electric field components in the cavity, the in-plane wave vectors are calculated and fitted to evaluate the cavity performance. The performance analysis of the cavity further proves the effectiveness of the optimization process. This has a guiding significance for the research of low threshold nano-laser.

1. Introduction

For the past few years, many researchers have paid their attentions to the Photonic Quasicrystal PQC [1]. And the Photonic Band Gap (PBG) is the most striking characteristics [2–4]. Moreover, the rotational symmetry and long-range patterns are apparent, which is distinguished from periodicity structure [5]. It is possible to confine the spread of electromagnetic fields in large areas, which demonstrated by photonic band gap theory in no defect local model [6]. Thus, a local pattern similar to the period structure can also introduce point defects or line defects in quasiperiodic crystals [7]. According to the PBG, the photonic cavities that strongly confine light are finding applications in many areas of physics and engineering.

According to Purcell effect [8], the rate of spontaneous emission depends partly on the environment of a light source. This means that by placing the light source in the nanocavity, the rate of spontaneous emission can be modified.

The Purcell factor represents the grade of the rate of spontaneous emission. The cavity is going to be used in a nanocavity laser filled with light-emitting materials, Purcell effect is a valid method to contribute toopticalgain and decrease the laser threshold. In another word, higher F_p means lower threshold. In order to increase Purcell factor, the parameters of the cavity were optimized. In certain conditions, the specific value of Q/V is determinant. Actually, we attempted to obtain a high-Q and low mode volume nanocavity.

Gathering predecessors' study result makes us able to deepen summarizing the rules of nanocavity design further [7,9–11]. We remove the central air-hole producing defects in two dimensional quasicrystal structures. Fine-tuning operations about the radius and the position of the air-hole is one of the most critical influences on higher Q factor. All of this credits to the theory of Slow-light. According to the Refs. [7,12], the Total internal reflection (TIR) occurring at the interface between the air holes and silicon is another key to obtain a higher Q.And the Bragg reflection has the same effect in the surrounding layers [7,13].

The effect of slow-light enhances the coaction of electromagnetic waves and the dielectric materials, which makes the nonlinearity more prominent [14]. As the position of the air-holes move, the normal modes of cavity approach the edge of the Brillouin zone, where the slow light comes into play. The definition of velocity in slow-light is the group velocity V_g, which describes the speed at an envelope propagates. According to T Baba's statement, V_g is greatly reduced by a large first-order dispersion arising from an optical resonance within the material or structure.

According to the Refs. [7,11], electromagnetic wave propagates through the defect, confined by total internal reflection in the vertical direction and Bragg reflection, due to the PBG, in the lateral direction. Owing to zone-folding of the guided-mode band and the coupling of forward and backward propagating waves forming a standing wave, the first-order dispersion diverges to infinity, and slow light occurs near a cut-off point called the band edge [14].

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There are two keys that should be concerned from T. Baba: delay-bandwidth product and higher-order dispersion. Delay-bandwidth product is the core of all the methods to realize slow-light. But the higher-order dispersion severely distorts optical signals. T. Baba tells us that a deep nested structure with different dispersion characteristics can effectively resist the influence of the higher-order in dispersion. According to Ref. [14], nested structure is more advantageous than a dispersion material. In this paper, we optimize the relationship of the radii between inner and outer air-holes to form nested structures to restrain higher-order dispersion.

In this work, a new structure is designedin Section 2 and theoretically investigated further to increase the Q factor by optimizing the geometrical parameters of the cavity as shown in Section 3. In addition, a smaller mode volume (V) was obtained. The Section 4 witnesses the method of Fourier Transformation (FT) to evaluate the performance of the cavity. Finally, Section 5 provides some conclusions. In the calculation, the modes of incident electromagnetic waves are all transverse electric (TE) mode. The Q factors and the field distributions (TE-mode) are obtained by using the Finite-Difference Time-Domain (FDTD) method and Finite Element Method (FEM), respectively.

2. The formation of 12-fold holographic PQC and nanocavity

The 12-fold PQC is formed by using the method of multi-beam common-path interference [15,16]. The interfering intensity distribution is expressed as

$$\mathrm{I(r)} = \sum_{j,l} E_j E_l * \exp\left\{-i[(\vec{k_j} - \vec{k_l}) \cdot \vec{r}]\right\} \tag{1}$$

where E_j is the amplitude of beam j, $\vec{r} = (x, y, z)$ is the spatial position vector. The wave vectors of 12 beams are:

$$\vec{k_m} = \frac{2\pi n_w}{\lambda}\left(\cos\frac{2(m-1)\pi}{12}\sin\varphi, \sin\frac{2(m-1)\pi}{12}\sin\varphi, \cos\varphi\right) \tag{2}$$

where m is corresponding to the ordinal number of beams, n_w is the refractive index of the medium in the writing laser wavelength, φ is the crossing angle between the light beam and z axis. Substitute $\varphi = 29^\circ, n_w = 1.5, \lambda = 0.355\ \mu\mathrm{m}$ into Eqs. (1) and (2), the holographic interferogram is shown in Fig. 1(a). In addition, the parameters here have a relationship with a Top-Cut Triangular Prism [15]. Besides, these parameters have nothing to do with simulation result.

The 2D PQC is composed of air-hole in silicon background. By removing the central hole, a nanocavity is obtained and the center area is shown in Fig. 1(b). The structural parameters are displayed in Fig. 1(b). It has been proved that the nanocavity without the central air-hole has a better performance on converging electromagnetic wave. The radii of the air-holes in the innermost ring is expressed as r and that of the other holes is indicated as R. The distance from the center of the cavity to the innermost ring is L.

3. Optimum design of cavity parameters

To obtain the high-quality nano-cavity, the Q factor and mode volume are optimized by finely adjusting the structural parameters r, R and L of the two cavities.

3.1. Q factorand mode volumevs.the parameters r, Rand L

Firstly, we investigate the isotropy of the PBG of 12-fold holographic PQC by finite-difference time-domain (FDTD) simulations. The spatial lattice positions of 12-fold PQC are given in Fig. 2(a), which are distributed on the x-y plane. Its modal characteristics performed by FDTD simulations indicate that the whispering gallery mode (WGM) can be sustained in this cavity.

To investigate its PBG effect, the transmission spectrum was calculate with effective index approximation. A source is put on one side. Then, the transmitted electromagnetic wave is detected on the opposite side. The calculated transmission spectrum is shown as solid curve in Fig. 2(b). In this figure, a significant PBG region from 200 nm to 1800 nm is observed. It is known that the extinction coefficient of silicon reduces to 0 over 1120 nm. In other word, the absorption spectrum is irrelevant to material loss performance from 1120 nm to 1800 nm. The light is confined in the special structure. Actually, we have calculated that the transmission coefficient is less than 0.1 with the radius of air-hole greater than 75 nm. In this case, the Q value calculated based on the equation $Q = \frac{f_0}{\Delta f}$ is not suitable for its limitations by the frequency step. In order to obtain accurate and reliable datum, in this work, we measure Energy Decay in Cavity to obtain Q. In order to simplify the calculation process, a model with the radius 10 μm is selected. In the calculation, $L = 1.20\ \mu\mathrm{m}$ keeps unchanged.

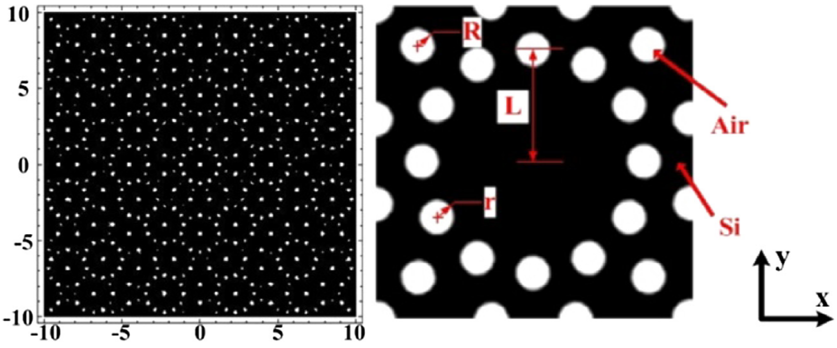
Since the stored energy of an isolated mode decays as

$$U(t) = U_0 \exp(-\alpha t) \tag{3}$$

where $\alpha > 0$, for a resonance centered at a frequency f, Q is simply

$$Q = \frac{2\pi f}{\alpha} \tag{4}$$

To use this method, the resonant mode is launched into the cavity, and a time-averaged energy density monitor can be used to calculate the stored energy in the cavity as the mode decays away.



(a) (b)

Fig. 1. (a) 12-fold holographic PQC without defect (b) the structural parameters of the cavity with defect.