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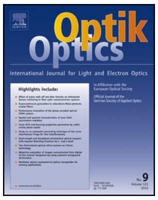

Original research article

Effect of thickness deviation on the absorption of graphene in photonic crystal microcavity

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ABSTRACT

The effect of thickness deviation on the optical properties of graphene-based optical microstructure was studied by using the transfer matrix method. Machining errors led to inconsistencies in the thicknesses of different parts and resulted in an offset of absorption peak, thus significantly reducing the average light absorption. The 3-nm deviation decreased the light absorption of graphene-optical microstructure by approximately 3.5 times. However, if the machining error is included in the design, then a relatively small Q value will help reduce the effect of machining error and the light absorption can be enhanced by about 32%.

1. Introduction

Two-dimensional materials, such as graphene, two-dimensional transition metal sulfide, and phosphorene, have excellent optical, electrical, and mechanical properties and are considered ideal materials for optoelectronics, especially flexible optoelectronic devices in the future [1–4]. However, the thickness of two-dimensional materials is usually less than 1 nm, and their light absorption and emission is relatively weak, greatly limiting their application for optoelectronic devices. However, due to their thinner dimension, two-dimensional materials can be combined with optical microstructures, such as photonic crystals, microcavities, and surface plasmas to form a composite structure of two-dimensional material-optical microstructure [5–36]. The light localization in these two-dimensional material-optical microstructure enhances the emission and absorption of two-dimensional materials.

Although many two-dimensional materials in optical microstructures have been designed, some of the composite structures are rarely used in actual production and application. Some experiments are carried out strictly in accordance with the theoretical design. However, the actual trapping efficiency of the theoretical trapping structure in the experiment is much lower than the theoretical result [5]. The biggest difference in the actual production is the existence of machining error. Machining error can cause certain deviations or roughness in the thickness of the dielectric layers of microstructures. The thickness deviation produces inconsistencies in the optical path of each part of the system so that the absorption peak of each part has a relative deviation, greatly reducing the average light absorption. However, in this paper, we show that if the machining error is included in the design, using a relatively small Q value will help reduce the effect of machining error and the light absorption will be enhanced by about 32%.

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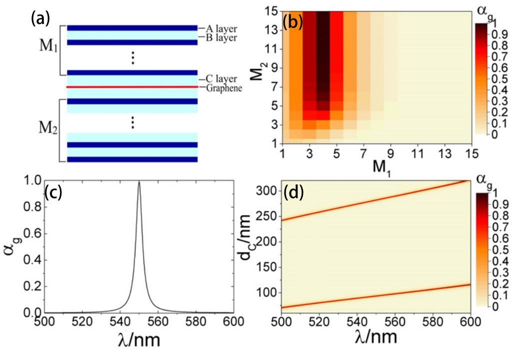

Fig. 1. (a) Schematic of graphene-photonic crystal microcavity structure; (b) the absorption of graphene at a wavelength of 550 nm varying with the periodicity of DBR mirrors on both sides of the microcavity; (c) the absorption of graphene varying with the change of wavelength; (d) contour map of absorption of graphene varying with the changes of wavelength and spacer thickness.

In this paper, the effect of machining precision on the optical properties of graphene-photonic crystal microcavity and found that the 3-nm machining bias allows light absorption reduction of graphene-photonic crystal microcavity from near 1 to about 0.28. Even at the best accuracy of routine experiment (i.e., about 0.5 nm, monolayer atomic thickness roughness) [37], the maximum average absorbance was only about 0.79. Thus, the effect of machining accuracy on the optical properties of graphene-optical microstructure is much larger than that of the traditional semiconductor microstructures such as quantum well. If the machining error is included in the design, a relatively small *Q* value will help to reduce the impact of machining errors and the light absorption will be enhanced. The main reason is that a higher *Q* value of optical microstructure corresponds to a smaller full width at half maximum (FWHM) of absorption peak. If the deviation of absorption peak is larger than the FWHM of absorption peak, the light absorption of two-dimensional materials are greatly reduced. This study provides guidance for the design of optoelectronic devices based on two-dimensional material-optical microstructure.

2. Numerical results

The composite structure of graphene-photonic crystal microcavity is shown in Fig. 1(a) and is composed of $(AB)^{M_1-1}ACGCA(BA)^{M_2-1}$ [11]. The C layer in the middle is a spacer layer, G is the graphene layer located at the center of defect layer, A (ZnS layer) and B (SiO_2 layer) are alternately distributed to construct a DBR mirror, and the periodicities are M_1 and M_2. The thicknesses of the A and B layers were $\lambda_0/4n_A$ and $\lambda_0/4n_B$, and the refractive indexes were n_A and n_B, respectively. In the calculations, the refractive index of the ZnS layer was 2.39, the refractive index of the SiO_2 layer was 1.46 [38], and the center wavelength $\lambda_0 = 550$ nm. C is also a SiO_2 layer, the thickness of which is $\lambda_0/4n_C - n\delta_g$, where n_C is the refractive index of the C layer, δ_g is the thickness correction due to the graphene layer in the microcavity, which was $\delta_g = 0.64$ nm, and n is the layer number of graphene.

First, we used the transfer matrix method [39,33] to study the effect of ordinary asymmetric microcavities on the absorption of graphene. In this structure, the periodicity M_1 and M_2 exhibited great influence on the absorption of graphene. When the periodicity of DBR mirror in the bottom part was greater than that in the upper part, the perfect absorption close to 1 could be obtained (Fig. 1(b)). Specifically, when $M_1 = 4$ and $M_2 = 10$, the maximum absorption of graphene was 0.991, and the FWHM of absorption peak was about 4.0 nm (Fig. 1(c)). Similar to other interference structures, the absorption peak of graphene in this structure could also be tuned by changing the characteristic thickness of the medium, such as by changing the thickness of interlayer C layer (Fig. 1(d)).

However, during the actual process of production, certain machining errors in the thickness of DBR mirror and spacer layer occur. As a kind of interference structure, the resonant wavelength is sensitive to the optical path or thickness of each layer, thus greatly influencing the absorption of graphene. In order to facilitate understanding, we first studied the effect of ladder-type spacer layer caused by machining errors on the absorption of graphene. The specific structure is shown in the inset of Fig. 2(a), whereby a ±1 nm thickness error in both sides of the ladder-type spacer layer occurred and the absorption peaks of graphene was blue- or red-shifted. When the spot of light was not very small, the light absorption was approximately the average of the three absorption curves and the absorption was greatly reduced, as shown by the red solid line in Fig. 2(a).

Furthermore, we considered the presence of certain deviations in the thickness of each layer in the photonic crystal microcavity. Normally, the deviation is Gaussian distribution $f(t) = e^{-\frac{t^2}{2\Delta^2}}/\sqrt{2\pi}\Delta$, where Δ is the standard deviation. Since the waving in each layer was similar to that in ladder-type spacer layer, we calculated each of standard variance 10,000 times and took the average absorption. At standard deviation $\Delta = 0.5$ nm, which is about the maximum accuracy that a laboratory can reach, that is, the thickness of an atomic layer, the absorption of graphene was evidently reduced, whereby the maximum average absorption was only 0.79 (Fig. 2(b)). At a standard deviation of $\Delta = 1$ nm, the maximum average absorption of graphene was only 0.59, which is consistent with the experiment results [5]. At $\Delta = 2$ nm ($\Delta = 3$ nm), the maximum average