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Volume-Confined Hyperbolic Polaritons and Surface-Confined Hyperbolic Polaritons in Ultrathin Hyperbolic Sheets and Their Identification

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Abstract

Recent numerical and experimental works have shown that both volume-confined hyperbolic polaritons (v-HPs) and surface-confined hyperbolic polaritons (s-HPs) can be excited in hyperbolic materials. However, the study of v-HPs and s-HPs in ultrathin hyperbolic sheets remains elusive. In this work, we show that the traditional methods, such as dispersion relation and distribution of electric field, are not able to identify the different types of HPs in ultrathin hyperbolic sheets. In consideration of the dispersion relation and distribution of electric field, this work indicates that v-HPs and s-HPs can be treated as the same HPs in ultrathin hyperbolic sheets. The electromagnetic waves in the hyperbolic materials are propagating waves and evanescent waves for v-HPs and s-HPs, respectively. Thus, the types of electromagnetic waves in hyperbolic sheets are the only method to identify the types of HPs. We believe that this work will deepen our understanding of the v-HPs and s-HPs, especially in ultrathin hyperbolic sheets.

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1. Introduction

Hyperbolic materials are extreme anisotropic materials, whose permittivity tensor has diagonal elements of not all the same sign.[1-6] They can support high-wavevector propagating waves and possess distinctive properties different from that of conventional materials, and thus they have attracted significant attention over the past few years.[7-13] So far, hyperbolic polaritons (HPs) have been discovered in natural hyperbolic materials, such as hexagonal boron nitride (hBN) and alpha-phase molybdenum trioxide (α-MoO_3).[14-23] The hyperbolicity makes hyperbolic materials good candidate for near-field optical imaging, focusing, negative refraction, and near-field radiative heat transfer.[24-37]

According to the types of the electromagnetic waves in hyperbolic materials, the HPs can be divided into two types: volume-confined hyperbolic polaritons (v-HPs) and surface-confined hyperbolic polaritons (s-HPs).[38-41] It has been numerically demonstrated that v-HPs and s-HPs can be simultaneously excited in hyperbolic materials with in-plane anisotropy.[38] In semi-infinite hyperbolic materials, multi orders of v-HPs can be excited, and thus v-HPs are in the form of continuous modes in the wavevector space. However, s-HPs can only be excited in certain wavevectors. Therefore, the v-HPs and s-HPs in semi-infinite hyperbolic materials can be easily identified in the wavevector space.[39] As far as we know, the v-HPs and s-HPs in ultrathin hyperbolic sheet have not been fully investigated, and their identification is not very clear.

In this work, taking hBN for an example, the v-HPs and s-HPs in ultrathin hBN sheets are investigated when its optical axis along the material surface. Our results indicate that the traditional methods, such as dispersion relations and distribution of electric field, cannot be used to identify the types of HPs excited in the ultrathin hBN sheets. In consideration of the dispersion relation and distribution of

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electric field, v-HPs and s-HPs can be treated as the same HPs. The results obtained in this work will deepen our understanding about the v-HPs and s-HPs in ultrathin hyperbolic sheets.

2. Results and discussion

hBN is a kind of natural hyperbolic materials whose permittivity tensor can be expressed as $\mathrm{diag}(\varepsilon_{||}, \varepsilon_{\perp}, \varepsilon_{\perp})$ when its optical axis is along *x*-axis. The explicit expression of $\varepsilon_{\perp}$ and $\varepsilon_{||}$ can be found in Ref. [9]. The hBN has two hyperbolic bands, the one between 1.47×10^{14} rad/s and 1.56×10^{14} rad/s is called the type I hyperbolic band in which $Re(\varepsilon_{\perp}) > 0$ and $Re(\varepsilon_{||}) < 0$, and the other between 2.58×10^{14} rad/s and 3.03×10^{14} rad/s is called the type II hyperbolic band in which $Re(\varepsilon_{\perp}) < 0$ and $Re(\varepsilon_{||}) > 0$. The plot of the permittivity can be found in lots of published literatures.[38] The structure considered in this work is shown in Fig. 1, where the thickness of hBN sheet is *h*. Both v-HPs and s-HPs are possible to be excited in different orientation due to the extreme in-plane anisotropy.[38]

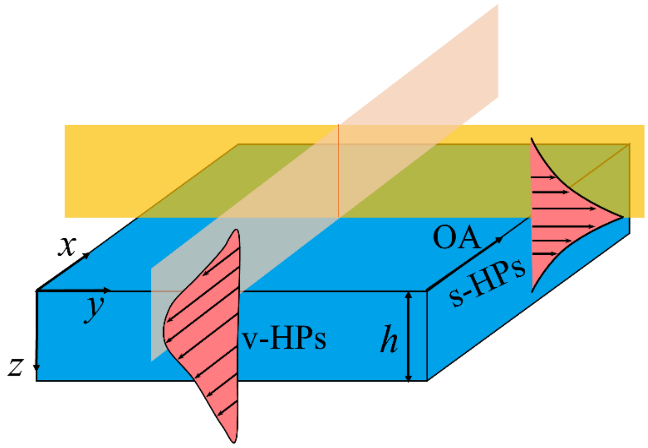

Fig. 1 Schematic of one hBN sheet with optical axis along the *x*-axis. Both v-HPs and s-HPs are possible to be excited in different orientation.

The HPs in hBN sheet can be found by investigating the imaginary part of the r_{pp}, as shown in Fig. 2. The r_{pp} describes the reflection of an incoming *p*-polarized wave into a *p*-polarized wave.[40] The angular frequency is 3×10^{14} rad/s and the thickness is 5 nm. The dispersion relation of HPs in thin hBN sheet can be derived and the analytical approximate relation is[42,43]

$$\beta = \frac{\rho}{k_0 h}\left[2\,arctan\left(\frac{\rho}{\varepsilon_{||}}\right) + \pi l\right],\ \ l = 0, 1, 2 \ldots \quad (1)$$

where

$$\rho = i\sqrt{\frac{\varepsilon_{\perp}\beta^2}{\varepsilon_{||}k_x^2+\varepsilon_{\perp}k_y^2}} \quad (2)$$

where k_x and k_y are the wavevector in the *x*- and *y*- axis, respectively. $\beta = \frac{(k_x^2+k_y^2)}{k_0^2}$ is the dimensionless wavevector in the *x*-*y* plane, where k_0 is the wavevector in vacuum. As shown in Fig. 2, it is clear the dispersion relations agree very well with the simulation when *l*=1. It is noted that Eq. (1) is applied for both v-HPs and s-HPs.[42] Therefore, it is not clear where is the v-HPs and s-HPs.

To identify the types of HPs, the electromagnetic waves in the hBN sheet are analyzed. In the hBN sheet, there is[43]

$$\frac{k_y^2+k_z^2}{\varepsilon_{||}} + \frac{k_x^2}{\varepsilon_{\perp}} = 1 \quad (3)$$

where k_z is the wavevector in the *z*- axis. When k_x and k_y are far larger than k_0, Eq. (3) can be rewritten as

$$k_z^2 = -\frac{\varepsilon_{||}}{\varepsilon_{\perp}}k_x^2 - k_y^2 \quad (4)$$

when the right side of Eq. (4) is positive, the electromagnetic waves in the hBN sheet are propagating waves, thus v-HPs are possible to be excited. When the right side of Eq. (4) is negative, the electromagnetic waves in the hBN sheet are evanescent waves, thus s-HPs are possible to be excited. At angular frequency of 3×10^{14} rad/s, there is $\varepsilon_{\perp} = -0.41 + i0.06$ and $\varepsilon_{||} = 2.83$. According to Eq. (4), v-HPs can be excited in the right and left sides of the origin, while the s-HPs can be excited in the up and down sides of the origin. The asymptotes between v-HPs and s-HPs should be $k_y = \sqrt{-\frac{\varepsilon_{||}}{\varepsilon_{\perp}}}k_x = 2.63k_x$, and they are shown in Fig. 2 as white solid lines.

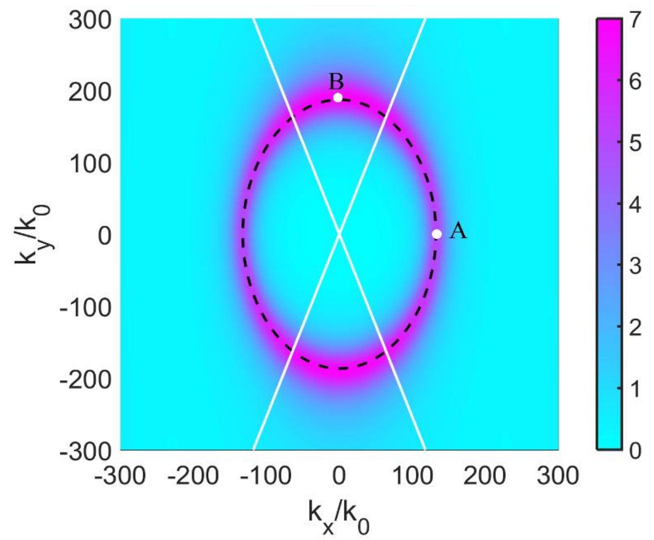

Fig. 2 (a) Imaginary part of r_{pp} in the k_x-k_y wavevector space at angular frequency of 3×10^{14} rad/s when the thickness of the hBN sheet is 5 nm. The white solid line corresponds to the asymptotes, while the black dashed curve corresponds to the 1-order HPs.

It is noted that the distribution of electromagnetic field is usually used to distinguish the types of HPs.[41,43,44] As shown in Fig. 3, the electric field along the *x*-axis at A (133, 0) and B (0, 190) is shown. The electric fields are almost identical in the hBN for A and B, while that are slightly different in the air. The fields decreasing exponentially away from the air/hBN interfaces. Therefore, the distribution of electric filed cannot be used to identify the types of HPs. In consideration of the dispersion relation and distribution of electric field, it seems that s-HPs and v-HPs can be treated as the same mode.

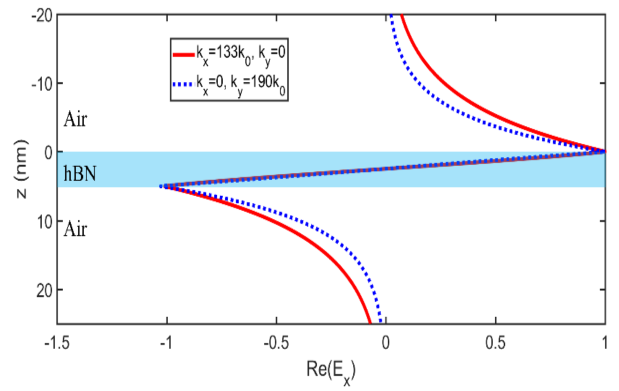

Fig. 3 (a) Normalized amplitude distribution of electric field along the *x*-axis. The angular frequency and wavevector are 3×10^{14} rad/s and the thickness is 5 nm.

When the thickness is 40 nm, the electric fields of A and B are shown in Fig. 4. One can see that the electric field of A oscillates in the hBN sheet, indicating the electromagnetic waves are propagation waves in hBN and the excited HPs are v-HPs in this case. Besides, one can see that the field of B in hBN decreases exponentially in the hBN sheet and is close to zero at the end of the sheet. The reason is that the propagation length of B in the hBN is 5.3 nm ($1/k_z$), and the thickness of the hBN sheet is much larger than the propagation length. The distribution of electric field in Fig. 4 can confirm the identification of s-HPs and v-HPs. Compared Fig. 4 with Fig. 3, one can see that the distribution of electric field of v-HPs and s-HPs are significantly different at large thickness, while they are almost the same at small thickness.

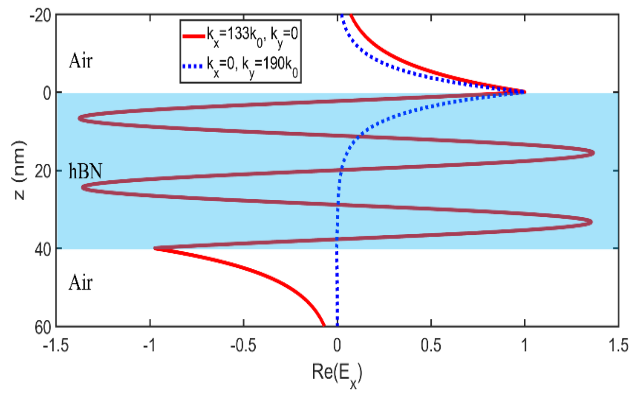

Fig. 4 Normalized amplitude distribution of electric field along the *x*-axis. The angular frequency and wavevector are 3×10^{14} rad/s and the thickness is 40 nm

3. Conclusions

We have investigated the v-HPs and s-HPs in ultrathin hBN sheets. The results have shown that the dispersion relations of v-HPs and s-HPs are identical in ultrathin hyperbolic sheets, thus the dispersion relation cannot be solely used to identify the types of HPs. Besides, even though the wavevectors of v-HPs and s-HPs are different in the hBN, it is found that the electric fields in hBN sheet are almost the same for v-HPs and s-HPs, thus the distribution of electric field cannot be used to identify the types of HPs. In addition, in terms of the dispersion relation and the electric field, the v-HPs and s-HPs seem to can be viewed as the same HPs. The electric fields of v-HPs and s-HPs in thick film are different, and thus they can be used to distinguish them. We believe that the results present in this work will deepen the understanding of v-HPs and s-HPs in hyperbolic materials, especially in ultrathin hyperbolic sheets.

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Supporting information

Not applicable.

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