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Enhancement of light-emitting efficiency of OLED by the electromagnetic-wave tunneling

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Abstract

In this Letter we present a new method enhancing the light-emission efficiency by electromagnetic-wave tunneling. The tunneling through negative-permittivity media has been confirmed recently. Under the conditions required by the method the transmittance of the emitted light can be close to unit for the normal incidence and also holds for the case of oblique incidence. The conditions of the tunneling for the proposed structure are given for E and H polarization, respectively.

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Keywords: Electromagnetic-wave tunneling; Organic light-emitting

Organic thin-film devices, such as light-emitting diodes (OLEDs), have attracted a great deal of attention [1], owing to the many appealing features that they possess and applications in practice. However, not all the luminescence produced in the organic layer can be emitted and much of them is lost and trapped in the layer via a variety of channels, among of which the guided mode [2], including surface plasmon–polariton (SPP) modes [3] that result from the coupling between the free charges at the surface of a metal and electromagnetic radiation [4] is the main factor that causes the reduction of external quantum efficiency. To overcome this problem many methods have been developed. Many of them are that introducing the periodic microstructure into the metal film [5,6] and the photoluminescence layer [7] or adding another corrugated dielectric overlayer on the cathode [8]. Furthermore, the efficiency can also be improved by the top-emitting structure [9]. The enhancement of the efficiency can be attributed to the Bragg scatter of the surface plasmon–polariton (SPP) and to the SPP cross coupling which permit the electromagnetic wave trapped in the layer to be extracted out partly and coupled into the light. However, these approaches are demanding in term of fabrication. Here we present theoretically a new approach to enhance the transmittance of the simple structure close to unit with the usage of electromagnetic-wave tunneling.

As far as the application of the electromagnetic wave tunneling is concerned, there have been some works devoted to its application [11], where the permittivity and permeability of the media are usually necessary to be negative simultaneously. The tunneling through only negative-permittivity media has been not reported until recently [12], which is characterized by the occurrence of high magnetic fields. In Ref. [12] a symmetric triple layers structure where the second layer has very large negative permittivity was investigated. With the transfer method a conclusion is drawn that if a given condition is satisfied the perfect transmission ($T = |t|^2 = 1$) will appear assuming that there is no absorption. Here the high transmittance through the film results form a new mechanism which is different from the excitation of surface plasmons (SPs) or the Fabry–Perot resonance, two usual ways introducing the high transmittance [13–16]. Now we try to find the perfect transmission conditions

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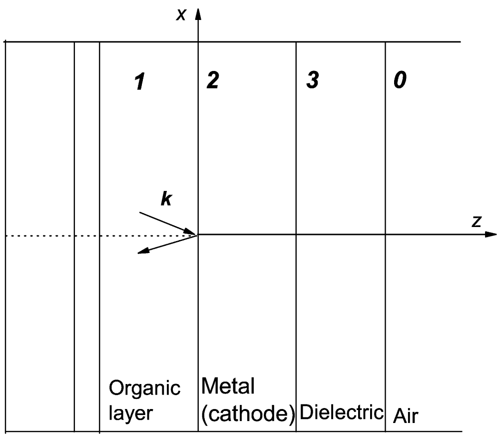

Fig. 1. Geometry of the system studied based on the top-emitting structure. The light is treated as incident from the layer 1.

of the asymmetric triple layers structure and apply it to enhancing light-emitting efficiency.

For the structure under the consideration as shown in Fig. 1. the first layer is the emissive layer as the common dielectric. The second one is the metal film with negative permittivity that used to be cathode and it is assumed that there only exists evanescent wave in it during the derivation. The third layer is another common dielectric adjacent to the semi-infinite air layer marked with 0. In the deviation the layer 1 is treated as semi-infinite because from which the light is created and emitted. Firstly we consider the case of TE wave incident on the interface between the layer 1 and 2 with the electric field vector perpendicular to the incident plane and the lights is assumed to be emitted form layer 1 with tangential component of the wave vector $k_x = \sin\theta_1 \omega\sqrt{\epsilon_1\mu_1}/c$. In term of transfer matrix method [17] we find that the reflection coefficient r is proportional to an expression as follows:

$$r \propto R_A e^{i\phi_A} - R_B e^{i\phi_B} e^{i(2k_{3z}d_3)}, \tag{1}$$

where $k_{lz} = \sqrt{(\omega/c)^2\epsilon_l\mu_l - k_x^2}$ $(l = 0, 1, 2, 3)$ is the component of wave vector $\vec{k}_l$ in the direction of normal of the interface in the layer l and ϵ_l, μ_l are permittivity and the permeability in layer l, respectively. The notations R_A, ϕ_A, R_B, ϕ_B are all the real multivariate functions of variables $d_2, k_{lz}, \mu_l(\epsilon_l)$ and independent of d_3 that is the thickness of the third layer, where $R_A, R_B > 0$. The unit transmittance means $r = 0$, i.e., Eq. (1) $= 0$. Note that the function R_A, ϕ_A, R_B, ϕ_B are all independent of d_3 and the factor $e^{i(2k_{3z}d_3)}$ can add a tunable phase $\Delta\phi$ $(= 2k_{3z}d_3)$ to ϕ_B so it is possible to realize

$$\phi_A + 2n\pi = \phi_B + \Delta\phi \tag{2}$$

by tuning d_3 solely and to make the condition $R_A = R_B$ satisfied at the same time, which gives the equation for TE wave as follows:

$$\begin{aligned} &k_{0z}\mu_0\left(\gamma^2\mu_1^2 + k_{1z}^2\mu_2^2\right)\left(k_{3z}^2\mu_2^2 + \gamma^2\mu_3^2\right)\cosh(2d_2\gamma) \\ &\quad + k_{0z}\mu_0\left(\gamma^2\mu_1^2 - k_{1z}^2\mu_2^2\right)\left(k_{3z}^2\mu_2^2 - \gamma^2\mu_3^2\right) \\ &\quad - 2\gamma^2 k_{1z}\mu_1\mu_2^2\left(k_{3z}^2\mu_0^2 + k_{0z}^2\mu_3^2\right) = 0, \end{aligned} \tag{3}$$

where $k_{2z} = i\gamma$, $\gamma = \sqrt{(\omega/c)^2|\epsilon_2\mu_2| + k_x^2}$ since $\epsilon_2 < 0$, $\mu_2 > 0$ for the metal and

$$\phi_A^{\mathrm{TE}} = \tan^{-1}\left[\frac{(k_{1z}k_{3z}\mu_2^2 + \gamma^2\mu_1\mu_3)\tanh(d_2\gamma)}{\mu_2\gamma(k_{3z}\mu_1 - k_{1z}\mu_3)}\right], \tag{4a}$$

$$\phi_B^{\mathrm{TE}} = \tan^{-1}\left[\frac{(k_{1z}k_{3z}\mu_2^2 - \gamma^2\mu_1\mu_3)\tanh(d_2\gamma)}{\mu_2\gamma(k_{3z}\mu_1 + k_{1z}\mu_3)}\right]. \tag{4b}$$

For a TM wave, in which the magnetic field is normal to the plane of incidence, the condition and the phases can be obtained from (3) and (4) simply by an interchange between permittivity ϵ and permeability μ

$$\begin{aligned} &k_{0z}\epsilon_0\left(\gamma^2\epsilon_1^2 + k_{1z}^2\epsilon_2^2\right)\left(k_{3z}^2\epsilon_2^2 + \gamma^2\epsilon_3^2\right)\cosh(2d_2\gamma) \\ &\quad + k_{0z}\epsilon_0\left(\gamma^2\epsilon_1^2 - k_{1z}^2\epsilon_2^2\right)\left(k_{3z}^2\epsilon_2^2 - \gamma^2\epsilon_3^2\right) \\ &\quad - 2\gamma^2 k_{1z}\epsilon_1\epsilon_2^2\left(k_{3z}^2\epsilon_0^2 + k_{0z}^2\epsilon_3^2\right) = 0, \end{aligned} \tag{5}$$

$$\phi_A^{\mathrm{TM}} = \tan^{-1}\left[\frac{(k_{1z}k_{3z}\epsilon_2^2 + \gamma^2\epsilon_1\epsilon_3)\tanh(d_2\gamma)}{\epsilon_2\gamma(k_{3z}\epsilon_1 - k_{1z}\epsilon_3)}\right], \tag{6a}$$

$$\phi_B^{\mathrm{TM}} = \tan^{-1}\left[\frac{(k_{1z}k_{3z}\epsilon_2^2 - \gamma^2\epsilon_1\epsilon_3)\tanh(d_2\gamma)}{\epsilon_2\gamma(k_{3z}\epsilon_1 + k_{1z}\epsilon_1)}\right]. \tag{6b}$$

Note that k_x is conserved on each interface when the wave transmits the structure and the conditions is angle-dependent theoretically for different incident angle θ_1.

With the above conditions obtained the case AB structure in Ref. [12] can be better understood where two layers, one of them being metal, are placed in the infinite isotropic medium, e.g., the air. Here we assume the permittivity of the semi-infinite medium on the both sides of the two layers are different, i.e., ϵ_1, ϵ_0 and all medium considered are nonmagnetic ($\mu = 1$) and $\epsilon_0, \epsilon_1, \epsilon_3 > 0$, $\epsilon_2 < 0$ are also assumed. According to Eq. (3) or (5) at normal incidence ($k_x = 0$), only if the inequality $\cosh(2d_2\gamma) > 1$ is satisfied can the thickness d_2 for perfect transmission exist, which equivalently gives the inequalities

$$\epsilon_0 > \epsilon_1, \quad \epsilon_0\epsilon_1 > \epsilon_3 \tag{7a}$$

or

$$\epsilon_0 < \epsilon_1, \quad \epsilon_0\epsilon_1 < \epsilon_3. \tag{7b}$$

The condition (7) describes the necessary configuration of the permittivity of the medium in each layer and does not involve ϵ_2. That means to get perfect transmission the permittivity of the semi-infinite medium on the both sides should not be equal each other and in addition the product of them should not equal to the permittivity of the nonmetal layer ϵ_3. In Ref. [12] because $\epsilon_0 = \epsilon_1$, $\cosh(2d_2\gamma) = 1$, $d_2 = 0$ for the AB structure and then perfect transmission cannot be realized, which is in accordance with Ref. [12].

Now let us consider an actual example where the values of the main parameters are taken from the Ref. [14]. In the following calculation $\epsilon_2 = -9.39$ which is the permittivity of silver at the wavelength 520 nm, the peak value in the spectra of Alq_3. The permittivity of emissive layer $\epsilon_1 = 3.24$ and the normal incident TE wave is assumed. Under the preceding parameter

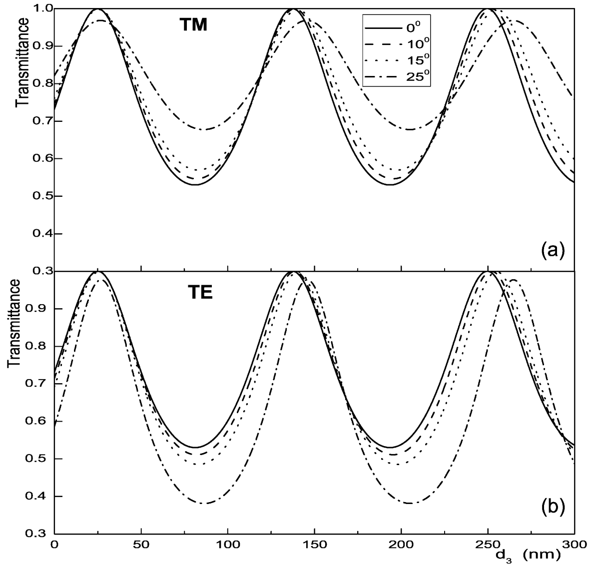

Fig. 2. Transmittance vs. d_3 with different incident angle 0°, 10°, 15°, 25° for TM and TE wave. The pertinent parameters: $\epsilon_1 = 3.24$, $\epsilon_2 = -9.39$, $\epsilon_3 = 5.36$, $d_2 = 10$ nm.

configuration the Eq. (3) is reduced into

$$\begin{aligned}&\gamma^2\big[k_0\big(k_1^2-\gamma^2\big)-2k_1k_0^2+k_0\big(\gamma^2+k_1^2\big)\cosh(2d_2\gamma)\big]\\&\quad+k_3^2\big[k_0\big(\gamma^2-k_1^2\big)-2k_1\gamma^2+k_0\big(\gamma^2+k_1^2\big)\cosh(2d_2\gamma)\big]\\&\qquad\equiv f_1(d_2)+k_3^2 f_2(d_2)=0.\end{aligned}\tag{8}$$

Note that in Eq. (8) k_3^2 is outside the square brackets and relatively independent if the two expressions in the square brackets have opposite signs for the parameters (d_2, k_1, γ) in a certain range the Eq. (8) can be satisfied with an appropriate k_3^2 and so can be the Eq. (2) simultaneously with appropriate d_3. With a simple calculation it is known in the range from 0 to 19.2 nm the two functions have opposite signs. If the thickness of the silver film in use d_2, for instance, is 10 nm, the permittivity of the layer ϵ_3 will be 5.36 according to Eq. (8) and at the same time $d_3 = \frac{2\pi n + (\phi_A - \phi_B)}{2k_3}$, where n is permitted to be all the integers that satisfy $d_3 > 0$ and in this case $d_3 = 25.0, 137.3, \ldots$. Fig. 2 shows the transmittance T of the structure vs the thickness d_3 with the numerical method. As the figure shown at the values 25.0, 137.3 the transmittance approaches to unit, in agreement with analytical results form Eq. (8). Here what is worth being pointed out is that for the TM wave under the same parameter condition we get the identical T vs. d_3 curve, which results from the normal incident and provides more practicality for application. Furthermore in the range $d_2 > 19.2$ nm where $f_1(d_2)$ and $f_2(d_2)$ have the same sign a dielectric with $k_3^2 < 0$, i.e., $\epsilon_3\mu_3 < 0$ can be used to satisfy the Eq. (3).

To investigate the influence on the conditions by the different incident angles the transmittance for the different θ_1 are also calculated and compared in Fig. 2. In the figure the T vs. d_3 curves with incident angle 0°, 10°, 15°, 25° are shown for TE and TM wave, respectively. Form Fig. 2 we can find out for a small range around the incident angle 0°, e.g., 0–15° the transmittance still keeps to be close to unit till the angle has a considerable deviation. For the large incident angle under the same parameter condition as the case of normal incidence there are still many peak values periodically but not close to unit. These can be explained noting that $R_A \neq R_B$ when Eq. (2) is satisfied periodically by d_3. In addition to the influence of the incident angle the lost as heat, which is one of important factors causing the power lost, is also estimated by considering the effect on the transmittance for the imaginary part of the permittivity. In Fig. 3 the transmittance T vs. wavelength λ is shown for TE and TM wave respectively with the dispersion relation of the silver considered over a relatively large range, where the dispersion curve is obtained by interpolation method with experimental data [18]. The parameters are set to satisfy the conditions Eqs. (3), (5) for the normal incidence with $d_3 = 25.0$ nm. The result indicates that even the real loss is considered the transmittance for the small angles is rather high when the tunneling condition is satisfied, here $T \sim 94.6\%$ at 520 nm.

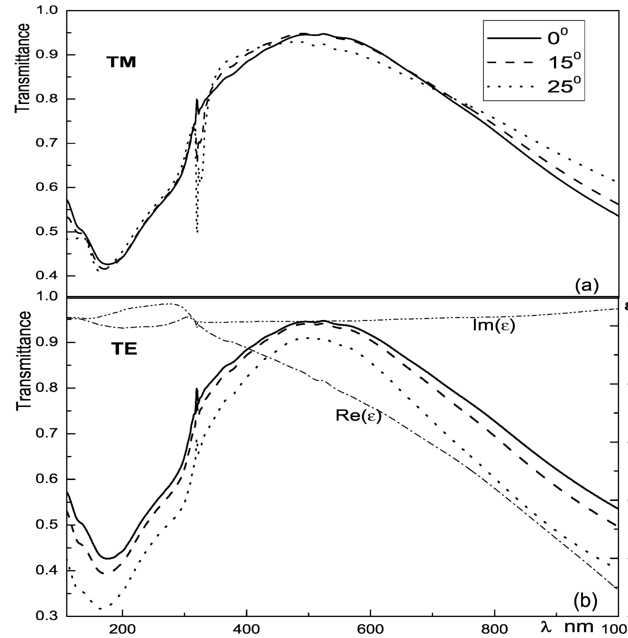

Fig. 3. (a) Transmittance vs. λ with different incident angle 0°, 15°, 25° for TM wave. (b) Transmittance vs. λ with different incident angle 0°, 15°, 25° for TE wave and the dispersion curve of the permittivity of the silver by interpolation with the experimental data.

Since the channels of the power lost are finite [9] and the power lost to the SPPs and to the guided modes have a large portion of the total power lost [8–10] it is believed that the energy trapped in the emissive layers with the form of the SPPs and the guided modes are extracted out efficiently with the losses as heat having been taken into account in mind when tunneling effect takes place.

In summary we have shown that for the organic light emitting structure a more simple method enhancing the light emitting efficiency than ever is now available just by tuning the thickness and permittivity (permeability) of the related materials. Though the condition of perfect transmittance is angle dependent, which brings the limitation to its application to some extent, the high enough transmittance and the stability for the incident angles in small range provide a considerable compensation for this disadvantage. These conditions for the tunneling effect can also be a assistant consideration based on the presented methods, e.g., the top-emitting structure [9]. Furthermore, because of the fabricating successfully of the media with negative permeability at visible frequency [19] and of the other optical materials, e.g., photonic crystals possessing effective permittivity the proposed method in the Letter is more feasible in practice.

Acknowledgements

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