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A novel proposal for enhancement of light extraction efficiency in WOLEDs based on optimized photonic crystal structures

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ABSTRACT

In this paper we propose a framework to enhance light extraction efficiency in white organic light emitting diodes (WOLED) using photonic crystal (PhC) structures sandwiched between indium tin oxide (ITO, n_{ITO} = 1.8+0.01i) and glass (n_{glass} = 1.51) substrate, according to the high refractive index contrast of these two layers almost 50% of the generated light inside WOLED gets trapped in the mentioned interface. The main purpose of this article is to suggest a method to intentionally optimize PhC structures to reduce total internal reflections (TIR) happening at ITO/glass interface. Here three different patterns are considered including rectangular, hexagonal and circular lattices. Using Finite Difference Time Domain (FDTD) method and the presented framework for choosing structural parameters the portion of 50% trapped light in ITO was reduced to 20% which is a large enhancement in extraction efficiency of WOLED. Also far-field results before and after adding PhCs are investigated.

1. Introduction

In recent decades, WOLEDs have been one of the most interesting fields of study [1], due to their attractive applications not only as flat panel displays but also as light illuminations, to the extent that, there is a possibility of introducing WOLEDs for the next generation of lighting systems instead of fluorescent and candescent lamps [2]. The advantages behind WOLEDs are consuming low power, having light weight, being thin and flat and also being environmental friendly because of using organic materials in its structure [3,4]. Generally, WOLED is made by layers, the first layer is substrate to support the WOLED and usually is made of glass, clear plastic or foil, the second one is a transparent anode made by natural graphite particles (ITO) which removes electrons and adds electron–hole when a current flows into the device, the next layer is the organic layer which is, in fact the active region in WOLED and the light is produced in it, and finally there is the cathode, usually made by Aluminum, which releases electrons when the current flows through the device [5]. There may be other excess layers to increase the quality of generated light or to improve the life time [6] as electron/hole transporting and blocking layers. The basic structure of a WOLED is shown in Fig. 1. In a WOLED the light is produced in the organic emissive layer due to the recombination of electrons and holes injected from electrodes so the efficiency of a WOLED is composed of the recombination efficiency of holes with electrons [5], the efficiency of WOLED using fluorescent emissive material is low because of selection rule limitation in which only singlet–singlet transition is allowed and the ratio of single exciton to the triplet in the electron–hole recombination process are only 1:3 [7,8] in the case of fluorescent emitter, 25% of internal quantum efficiency (IQE) which correspond to 5% of external quantum efficiency (EQE) can be obtained from the 25% of the singlet spin state. When a phosphorescent emitter is applied, the remainder 75% of triplet spin states can also emit light. Therefore an IQE of 100% (which correspond to the 20% of EQE) can theoretically be obtained [7], though the IQE of a WOLED has already reached 100% through careful design of the device structure [8,9].

In spite of all these achievements, a big problem still exist, which prevents WOLED from being commercially introduced and that is its low External Quantum Efficiency (EQE), which is only about 20% [10]. In fact about 80% of the generated light in active region cannot reach out to the air due to TIR happening in inner interfaces, the sizeable portion of light which is 50% reflects back in to the anode because of refractive index difference between glass (n_{glass} = 1.51) and ITO (n_{ITO} = 1.8 + 0.01i), and the remaining 30% is trapped in glass–air interface again because of TIR [11]. Here we focused on

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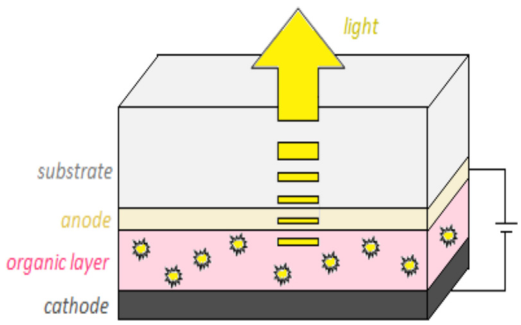

Fig. 1. The basic structure of WOLED.

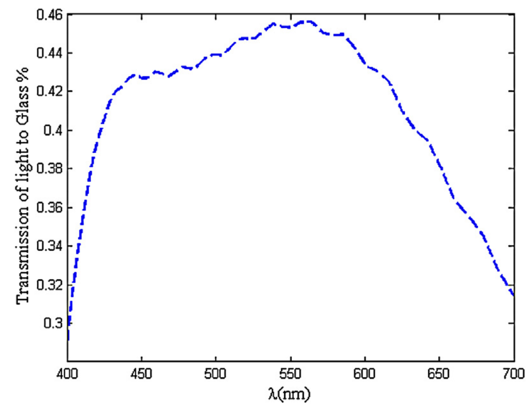

Fig. 2. Transmission of light to the glass substrate without applying PhC.

reducing the portion of TIR in ITO–glass interface because a large amount of light is trapped here and cannot couple to the glass and finally to the air. In order to decrease the amount of TIR in glass–air interface one can use micro-lenses arrays [12,13] and get even better EQE. So far lots of efforts have been reported to reduce TIR in ITO–glass interface, such as using rough internal interfaces [11], high index substrate with micro-lenses arrays [12], using optimized multilayer structures [14], quasi photonic crystals [15] and photonic crystals [16,17].

In this study, our main attempt is to present general framework to optimize PhC structures in order to reduce TIR happening in ITO–glass interface. Three different patterns are optimized for the lowest TIR or on the other hand the highest transmission. Besides the effect of each pattern on the far field profile of WOLED is presented and discussed.

2. Simulation & results

The aim of this research is to present a general framework to specify the PhCs parameters so to get best extraction efficiency using PhC patterns in ITO–glass interface. As PhCs are multi-parameter structures, their optimization is a hard task but considering some important rules helps to estimate best parameters for achieving wanted goals. The framework is that to get more transmitted light to the glass substrate or in other words to reduce the TIR happening in ITO–glass substrate there are some rules. Following these rules will help to get the optimized structure to achieve the best transmission and then in order to confirm the validity of the presented framework three different patterns are optimized. In the framework presenting in this research we claim that: First, the height of backfill and rods must be reasonable, in order not to affect electrical properties of WOLED. Second, much more increment or decrement of parameters will not always guarantee the achievement of better results, for example increment of height of rods only for limited values enhances transmission. Third, the lattice constant should be close to the vacuum wavelength of incident light [16], and finally if the Brillouin zone get closer to circle there will be more transmission and better results [16]. To prove our claim we started with basic structure of WOLED and then added rectangular, hexagonal and circular lattices to the ITO–glass interface. The outcomes showed that the maximum transmission that is achieved for each structure follows the framework's rules.

In this research, Finite Difference Time Domain (FDTD) method is used to simulate three different patterns including rectangular, hexagonal and circular PhCs which are applied to the ITO–glass interface, each of patterns are optimized to give maximum transmission of light to the glass substrate. In all structures the shape of rods are circular and the material used for rods and backfill are SiO_2 $n_{sio_2} = 1.46$ and SiN_x $n_{SIN_x} = 1.95$ respectively. In this research all layer's absorption and also dependency of refractive indexes to wavelength are considered whereas in the previously reported researches the refractive indexes were constant for simplicity [16]. The point source which is active for 20 fs and in the range of 400 nm 700 nm best models the behavior of a WOLED, considering 100% IQE [16]. Each side of the structure is modeled by perfectly matched layer (PML), except the metal cathode which is modeled by metal boundary condition to model its fine reflectivity and the mesh sizes are $\Delta x = 15$ nm, $\Delta y = 15$ nm and $\Delta z = 10$ nm, the monitor in glass substrate shows the transmission, also here we measured the absorbed light in the layers of WOLED, which is lost and out of reach.

In the first step, the basic structure of WOLED without applying PhC is simulated, as shown in Fig. 1, in which the outcome of the simulation is compatible with the previous theoretical results [16]. The portion of 50% transmitted light to the glass substrate is illustrated in Fig. 2. About 3% of light is absorbed before getting in to glass substrate in internal layers and is out of reach because of the imaginary part in ITO's refractive index which indicates the absorption.

The far field profile of the basic WOLED without applying any PhC, is also demonstrated in Fig. 3 for blue, green and red (BGR) spectrums. The results illustrate that the light is distributed almost uniformly at the center (position of point source) and is not diffracted in any special direction due to not applying any PhC.

In the next step the WOLED with rectangular PhC applied to the ITO–glass interface is investigated. Fig. 4 shows the WOLED structure with PhC.

Rectangular pattern of PhCs applied to the WOLED has been already studied [15], but in this research, this is studied for all visible light wavelength range whereas in other previous reports have been studied only for single wavelength of 560 nm. We deliberately analyzed rectangular PhC's effect on WOLED's extraction efficiency to examine whether it is possible to get better results than the optimized structure previously introduced on [16] or not. The best results for transmission of light in to glass substrate and far field profiles for BGR after adding rectangular PhC to WOLED are indicated in Figs. 5 and 6 respectively, selecting the optimized parameters according to the amounts represented in the inset of Fig. 5 gives a large enhancement of about 20% more extraction

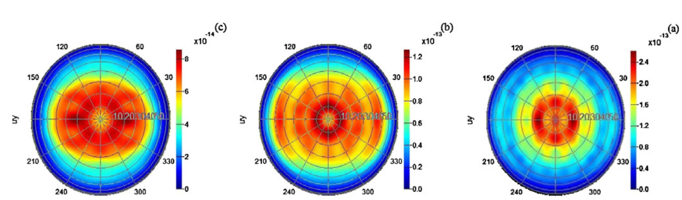

Fig. 3. Far field profiles of WOLED without PhC, (a), (b) and (c) for 470, 560 and 600 nm respectively.