Optimal design and experimental realization of DBR-metal microcavity organic lasers

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ABSTRACT

Optical microcavity is a high quality factor micro-cavity with a size of the resonant wavelength. By using of spontaneous emission modulation of organic gain medium, an organic microcavity laser can be achieved. In this paper, a metal Ag-dielectric DBR mirrors mixed organic micro-cavity structure was proposed in this paper. And the influences of center wavelength, growth sequence and the cycle number of DBR, and the thickness of Ag mirror and organic light-emitting layer on performance of Ag-DBR mixed organic micro-cavity were investigated by simulation. And then according to PL characteristics of Alq3:DCM(0.5wt%), an optimal metal Ag-DBR microcavity structure was designed, and based on theoretical calculation results, a corresponding microcavity devices (air/Ag/organic layer/DBR/glass) was fabricated. The experimental and theoretical simulation results are in good agreement. The results show that the calculation method of ours is of great guided significance on the fabrication of metal-DBR organic microcavity lasers.

Key words：Microcavity, organic semiconductor laser (OSL), metal film mirror, distributed Bragg reflector(DBR)

1 INTRODUCTION

Optical microcavity is a high quality factor micro-cavity with a size of the resonant wavelength. A microcavity can modify the spontaneous emission properties of the materials inside spatially and spectrally owing to the alteration of the optical mode density within it. As a consequence, the interaction between material and light within the microcavity was changed greatly compared with the condition of free space, which is called "Purcell" effect [1]. D. Kleppner proposed that spontaneous emission can be controlled by resonator in early of 1980's, which greatly reduces the lasing threshold, and is expected to achieve non-threshold lasers [2,3,4].

As a new laser gain media, organic semiconductor materials have been paid attention to in recent years. By using of spontaneous emission modulation of organic gain medium, an organic microcavity laser can be achieved [5,6,7]. Since 1996, how to obtain the electrically-pumped lasers has been the major research goal. The major challenges are low carrier mobilities of organic films together with additional losses owing to contacts, carrier absorption, and other

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nonradiative mechanisms, which limit the thickness of organic films to thin layers and introduces serious optical losses in a planar waveguide or distributed-feedback(DFB) structure[8,9,10]. One promising structure for electrically pumped OSLs is a microcavity structure that is formed by depositing one or multilayer organic materials between two mirrors separated by a few hundred nanometers [11], which will be helpful to reduce the threshold of organic lasers[12].

In this paper, a metal Ag-dielectric DBR mirrors mixed organic micro-cavity structure was proposed. Compared to DBR-DBR structure and metal-metal reflector micro-cavity structure, the Ag-DBR mixed organic micro-cavity has less losses and easy to fabricate. The influences of center wavelength, growth sequence and the number of cycles of DBR, and the thickness of Ag mirror and organic light-emitting layer on performance of Ag-DBR mixed organic micro-cavity were investigated by simulation. And then according to PL characteristics of Alq3: DCM (0.5wt%), an optimal Ag-DBR microcavity was designed, and based on theoretical calculation results, a corresponding micro-cavity devices (air/Ag/organic layer/DBR/glass) was fabricated. The experimental and theoretical simulation results are in good agreement. The results show that the calculation method of ours is of great guided significance on the fabrication of metal-DBR organic microcavity lasers.

2. THEORY MODEL

The structure of Ag-DBR microcavity and molecular structure of organic materials shown in Fig.1 and Fig.2,respectively. In which, DBR composed of Quarter-wavelength-stacks (QWS) of alternating ZnS/MgF2 dielectric film as a bottom mirror, Ag films as a top mirror, and DCM(0.5wt%) doped of Alq3 as the laser gain medium.

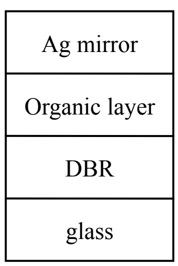
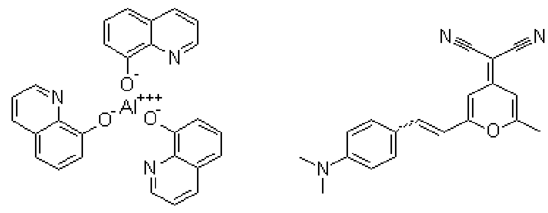


Fig.1 Structure of Ag-DBR microcavity



Alq_3 DCM

Fig.2 Molecular structure of the organic materials used

The growth sequence and the cycle number of DBR will directly affect DBR's reflectivity and microcavity mode. The stop bandwidth of DBR is an important performance. In order to get good optical constraint, the stop bandwidth of DBR should cover the entire free space PL spectral range of organic materials. The width of the stop band is estimated by [13,14]:

$$B \approx \frac{\Delta n}{n} \cdot \lambda_0 \tag{1}$$

Where Δn is the index difference between the layers that constitute the stack, n is the average index, and λ_0 is the center wavelength of the stop band. The peak reflectivity of the DBR is given by[12]:

$$R_d = \tanh \sum_i \tanh^{-1}(r_i) \tag{2}$$

Where r_i is the index difference between a pair of layers in the stack.

Presume that light emitted along the optical axis, only when the wavelength of light satisfy the relationship (3), the cavity optical resonance mode is allowed to exist in microcavity[12]:

$$m\lambda_m = 2L(\lambda) \tag{3}$$

where m is the mode index, λ_m is the peak wavelength for the cavity, and L (λ) is the effective resonator cavity length. By adjusting the optical path, model number and the mode positionl will change. The total effective optical length of the cavity, L (λ) is given by[12]:

$$L(\lambda) \approx \frac{\lambda}{2}\left(\frac{n_{eff}}{\Delta n}\right) + \sum_i n_i d_i + \left|\frac{\varphi_m}{4\pi}\lambda\right| \tag{4}$$

The first term m in Eq.(4) is the penetration depth of the electromagnetic filed into the dielectric, the second term is the sum of optical thickness of the organic layers between two mirrors, and the last term is the effective penetration depth into the top metal Ag mirror. The phase shift at the metal reflector (φ_m) is given by: [12]:

$$\varphi_m = \arctan\left(\frac{2n_s k_m}{n_s^2 - n_m^2 - k_m^2}\right) \tag{5}$$

where n_s is the refractive index of the organic material in contact with the metal, and nm and km are the real and imaginary parts of the refractive index of the metal. Inferred from the formula (3) and (4), we can see, metal thickness, reflectivity, DBR reflectivity and the thickness of the organic layer have a great impact on the cavity performance. When the DBR is made, the first and second term of formula (4) remain basically unchanged. So the cavity length can be adjusted by changing the thickness of the organic layer.

The FWHM of microcavity emission as a first approximation by equation (6) estimate [15]

$$\Delta\lambda = \frac{\lambda^2}{2n_{eff}L}\cdot\frac{1-\sqrt{R_d\cdot R_m}}{\pi\left(R_d\cdot R_m\right)^{1/4}} \tag{6}$$

where L is the effective length of the cavity, and n_{eff} is the effective refractive index of the microcavity, and R_d and R_m are the reflectivity of DBR and Ag mirror, respectively.

The microcavity quality factor, Q and the peak enhancement factor, F can be calculated by: [16]

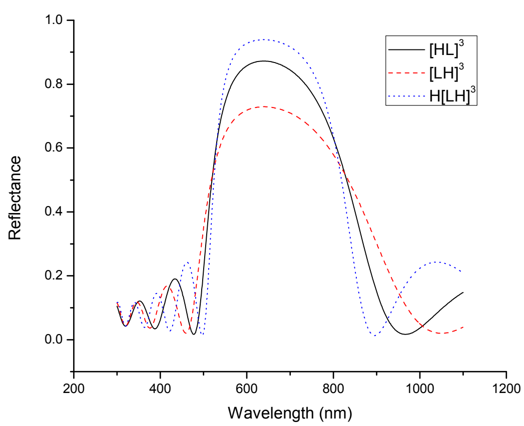
$$Q = \frac{\lambda}{\Delta\lambda} = m\cdot\frac{\pi\left(R_d R_m\right)^{1/4}}{1-\sqrt{R_d\cdot R_m}} \quad , \quad F = \frac{Q}{m} = \frac{\pi\left(R_d\cdot R_m\right)^{1/4}}{1-\sqrt{R_d R_m}} \tag{7}$$

During the calculation process, all components of the R_d and R_m are the same, so F is a constant. With the increase of cavity length, mode number increased, but every single mode of the enhancement factor decreased.

3. RESULTS AND DISCUSSION

3.1 The growth sequence effect on reflection spectrum of DBR

ZnS (n = 2.3) and MgF2 (n = 1.38) as high and low refractive index material were selected to fabricate DBR mirror. The calculated results shows that QWS growth sequence have a significant impact on DBR reflection spectrum, shown as Fig. 3. When the thickness error of DBR layers within 5%, it can be ignored.



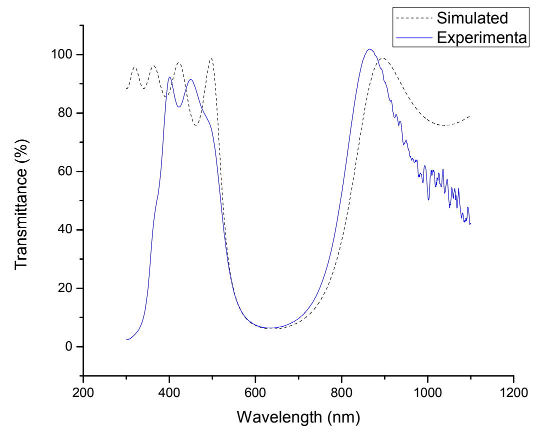
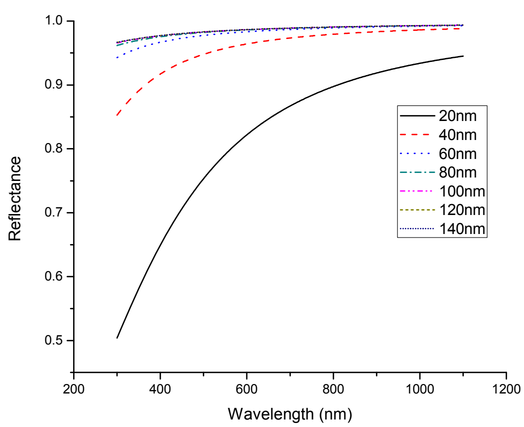


Fig.3 DBR reflection spectrum with different growth

Fig.4 The simulated and experimental transmission spectrum of H[LH]^3

3.2 Determination of thickness of Ag mirror

With the varying of Ag film thickness, the reflectivity, the phase shift at metal interface change too, which will has affect on the cavity performance, such as Fig.5, Fig. 6 below. Simulation results how that, when the Ag film thicker than 80nm, the reflectivity spectrum and reflection phase shift is almost unchanged. Therefore, the thickness of Ag mirror is taken to 100nm below.



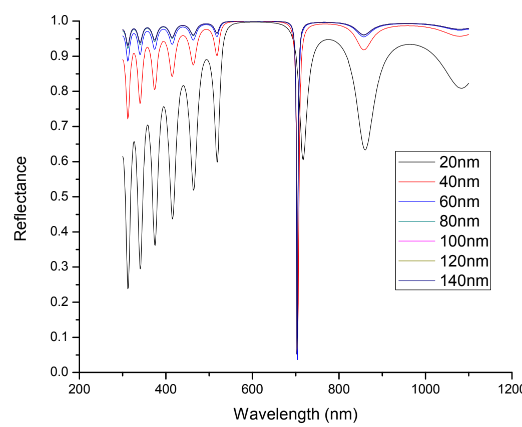


Fig.5 The reflection spectrum of Ag mirror

Fig. 6 The reflection spectrum of microcavity glass/DBR([HL]^5)/Ag

3.3 Determination of the organic layer thickness

According to the formula (4) and (5), the DBR penetration depth is 644.35nm, and Ag mirror penetration depth is 39.52nm, and sum of them is 683.87nm, which greater than the peak wavelength of PL spectrum of Alq3:DCM (n =1.72). So the effective cavity length of micro-cavity can only be $L_{eff} = 3\lambda / 2$, 2λ, $5/2\lambda$……When Leff = $3\lambda / 2$ (m = 3) and Leff = 2λ (m = 4), the reflection spectrum of cavity were calculated with different thickness of organic layer, shown as Fig.7 and Fig.8.The optimum thickness of organic layer calculated to be 166nm and 352nm, respectively.

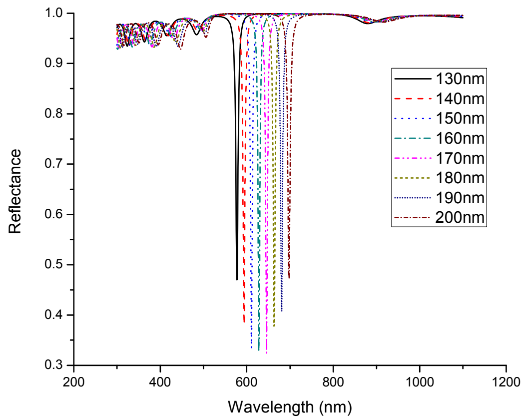


Fig. 7 The reflection spectrum of 3λ/2 cavity with different thickness organic layer

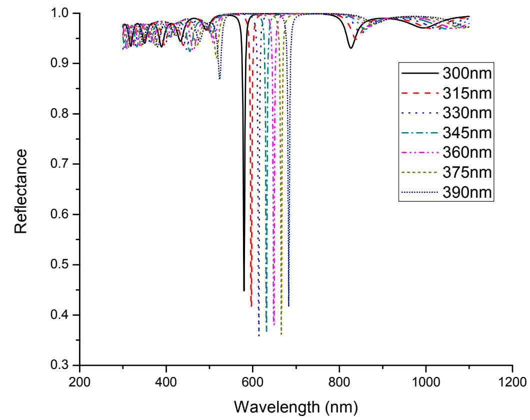


Fig. 8 The reflection spectrum of 2λ cavity with different thickness organic layer

3.4 Experimental results

In accordance with the above results, the H[LH]^^{3} ZnS/MgF2 DBR was prepared on cleaned glass substrate, in which the thickness of ZnS layer is 74.6nm, and the thickness of MgF2 is 122.3nm (corresponding to the quarter center wavelength of λ_0=639nm). Then the transmission spectrum of the DBR was probed with HITACHI U-3010 UV-VIS spectrometer, and the ZnS/MgF2 DBR reflection spectrum with center wavelength of 639nm was calculated too. Both of them are in good agreement, shown as in Figure 4.Then evaporated Alq3: DCM (0.5%) organic film which thickness is take to166nm, and finally deposited Ag mirror on it.

Then the microcavity sample pumped by YAG (355nm/5.5ns/10Hz) laser, and probed with SphereOptics(model SLM-12) fiber spectrometer vertical to the surfaces. The results shown in Figure 10, the peak wavelength of lasing at above 635nm, and its FWHM~7nm, which in good agreement with the calculated values.

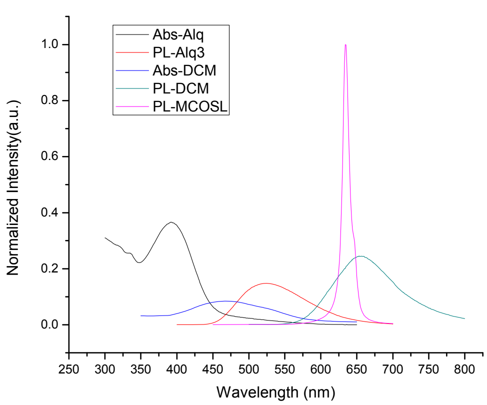


Fig. 9 The absorption spectrum, PL spectrum and emission spectrum of Alq3, DCM, Alq3:DCM and microcavity

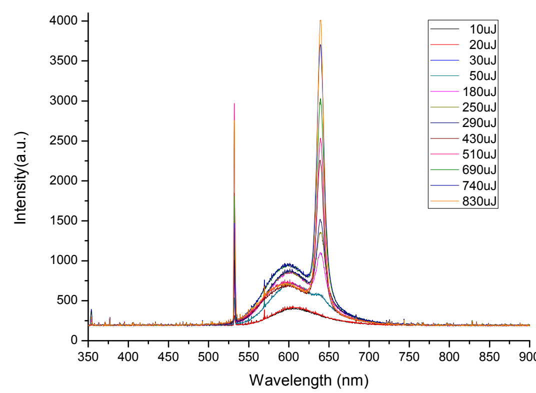


Fig.10 The emission spectra of microcavity pumped by YAG(355nm/5.5ns/10Hz) laser

4. CONCLUSIONS

In conclusion, a metal Ag-dielectric DBR mirrors mixed organic micro-cavity structure was proposed in this paper. And the influences of center wavelength, growth sequence and the number of cycles of DBR, and the thickness of Ag mirror and organic light-emitting layer on performance of Ag-DBR mixed organic micro-cavity were investigated by simulation. And then according to PL characteristics of Alq3:DCM(0.5wt%), an optimal metal Ag-DBR microcavity structure was designed, and based on theoretical calculation results, a corresponding microcavity devices (air/Ag/organic layer/DBR/glass) was fabricated. The experimental and theoretical simulation results are in good agreement. The results show that the calculation method of ours is of great guided significance on the fabrication of metal-DBR organic microcavity lasers.

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