Design of integrated microlens for collimation of the vertical-cavity surface emitting laser array*

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A method based on the theory of transfer matrix to design the integrated microlens for the collimation of vertical-cavity surface emitting laser (VCSEL) array is presented. The integrated microlenses fabricated on the substrate directly and on a certain polymer material which is on the substrate are considered. The relationships between the radius of curvature, beam waist and the divergence angle after collimation are obtained with the help of ZEMAX. The results show that the devices with the divergence angle of 15° ($1/e^2$) and beam waist of 2 μm can be improved to those with the divergence angle lower than 1°, and the devices with beam waist of 10 μm can be improved to those with the divergence angle lower than 3°, which is a good reference for manufacturing high-power devices with small divergence angle. The conclusions including increasing the thicknesses of both the substrate and polymer material and reducing the diameter of oxidized layer are drawn, which will be an important guidance for experiment research.

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Although the far-field divergence angle ($1/e^2$) has been greatly improved for vertical-cavity surface emitting lasers (VCSELs) compared with edge emitting lasers, it is still as large as 10°-20°. It is impossible to use such devices directly in those fields which need good beam quality such as optical interconnection, space telecommunication, lidar and etc. Hence, the collimation for such devices is inevitable. Traditional optics gives good suggestions for such a problem[1,2]. However, the separated collimation elements cause great trouble for adjustment[3,4] and assembling as well as the cost and thus integrated microlens has been investigated.

The microlens is integrated either directly on the substrate of VCSELs or on a certain kind of polymer material which is deposited on the substrate or the top of VCSELs. Yongqi Fu et al[5] reported the divergence angle of 0.3° ($1/e^2$) and 4 mW output power with hybrid microlens on the substrate directly; Si-Hyun Park et al[6] reported stable single fundamental mode and 3 mW output power with InGaP microlens on the top of VCSELs; Christophe Levallois et al[7] reported the divergence angle of 2.8° (FWHM) with SU-8 microlens on the substrate. Yet, they have been only focused on the devices with fixed diameter of oxidized aperture and thickness of the substrate which neglected the relationship between devices and microlens and resulted in low beam power after collimation. Moreover, the methods to determine the radius of curvature usually consume large amount of time and cost. In order to fabricate the integrated microlens more specifically, this paper will mainly discuss the design method of the integrated microlens fabricated both on the substrate directly and on a certain polymer material which is on the substrate. Meanwhile, new ways to VCSELs with higher power and lower divergence angle are explored.

Fig.1 is the schematic diagram of VCSEL array with integrated microlens fabricated directly on the substrate, which includes the upper Au contact, P-DBR, oxidized layer, active layer, N-DBR, substrate and lower electrode.

Here, l is the wavelength in vacuum; q_1 is the divergence angle ($1/e^2$) without collimation; W_0 is the diameter of the oxidized layer; W_1 is the beam waist before microlens; W is the diameter of the emitting aperture; L is the period of the array; S_1 is the thickness of the substrate; n is the index of the substrate as well as microlens; H, R and f are the diameter, radius of curvature and focal length of the microlens, respectively. It is obvious that the following constraint con-

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ditions have to be satisfied

$$W \leqslant H < 2R \leqslant L\ , \tag{1}$$

$$f = R/(n-1)\ . \tag{2}$$

After collimation, the beam has a divergence angle ($1/e^2$) of θ_2 and beam waist W_2 located in a distance of S_2 away from the microlens.

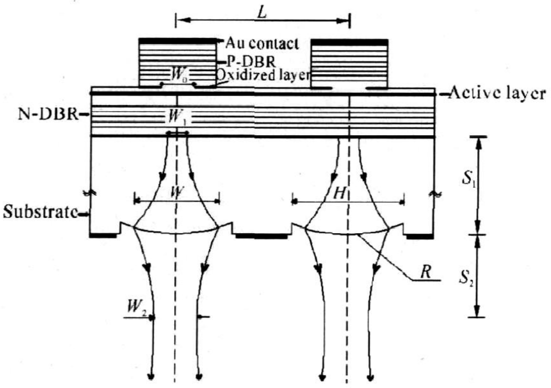


Fig.1 Schematic diagram of VCSEL array with integrated microlens on the substrate

The q parameter of Gauss beam[8] in a complicated system can be expressed by a transfer matrix,

$\begin{pmatrix} A & B \\ C & D \end{pmatrix}$:

$$q_2 = (Aq_1 + B)/(Cq_1 + D)\ , \tag{3}$$

where the q parameter is defined as

$$\frac{1}{q_i} = \frac{1}{R_i} - \mathrm{i}\frac{\lambda_i}{\pi W_i^2}\ ,\quad i = 1,2\ , \tag{4}$$

$$\lambda_2 = \lambda = n\lambda_1\ . \tag{5}$$

For the microlens fabricated directly on the substrate, we have

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & S_2 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -\dfrac{1}{f} & n \end{pmatrix}\begin{pmatrix} 1 & S_1 \\ 0 & 1 \end{pmatrix} =$$

$$\begin{pmatrix} 1-\dfrac{S_2}{f} & S_1 - \dfrac{S_1 S_2}{f} + S_2 n \\ -\dfrac{1}{f} & -\dfrac{S_1}{f} + n \end{pmatrix}\ . \tag{6}$$

Based on Eqs.(1)-(5), for the entrance beam and the exit beam which are both located at their beam waists, we can get

$$W_2 = \frac{nfW_1}{\left[(S_1 - nf)^2 + \dfrac{\pi^2 n^2 W_1^4}{\lambda^2}\right]^{\frac{1}{2}}}\ . \tag{7}$$

When $S_1 - nf = 0$, that is, for

$$R = \frac{n-1}{n} S_1\ , \tag{8}$$

we can get the maximum W_2 which indicates the minimum divergence angle θ_2 after collimation, since it is inversely proportional to the beam waist for Gauss beam. And now,

$$W_2 = \frac{f\lambda}{\pi W_1}\ , \tag{9}$$

that is, $W_2 \propto f$, $W_2 \propto 1/W_1$, which means that for a thicker substrate and a smaller beam waist, a larger beam waist and smaller divergence angle after collimation will be obtained.

Now, the situation that the microlens is formed on a certain kind of polymer material deposited on the substrate is considered. In Fig.2, the polymer material has the index of n_1 and thickness of h; R, f and S_1 are the same with the above while S_2 is now the distance between the beam waist after collimation and the polymer microlens.

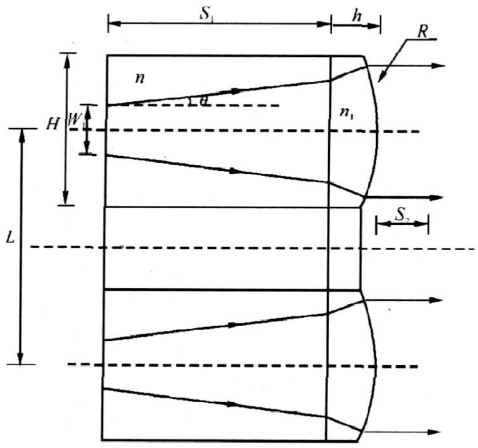


Fig.2 Schematic diagram of the integrated microlens on polymer material deposited on the substrate

Here, we have

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & S_2 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -\dfrac{1}{f} & n_1 \end{pmatrix}\begin{pmatrix} 1 & h \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & n/n_1 \end{pmatrix}\begin{pmatrix} 1 & S_1 \\ 0 & 1 \end{pmatrix} =$$

$$\begin{pmatrix} 1-\dfrac{S_2}{f} & S_1 + \dfrac{nh}{n_1} - \dfrac{nhS_2}{n_1 f} - \dfrac{S_1 S_2}{f} + S_2 n \\ -\dfrac{1}{f} & -\dfrac{S_1}{f} - \dfrac{nh}{n_1 f} + n \end{pmatrix}\ . \tag{10}$$

Similarly, we can get

$$W_2 = \frac{nfW_1}{\left[n_1^2 S_1^2 + 2nn_1 hS_1 - 2nn_1^2 fS_1 + n^2h^2 + n^2n_1^2 f^2 - 2n^2 n_1 fh + \frac{\pi^2 n^2 n_1^2 W_1^4}{\lambda_2}\right]^{\frac{1}{2}}} . \quad (11)$$

To get the condition for the maximum W_2, let's consider the condition for the minimum of the expression $n_1^2S_1^2+2nn_1hS_1-2nn_1^2fS_1+n^2h^2+n^2n_1^2f^2-2n^2n_1fh$ in the denominator. We get

$$f = \frac{S_1}{n} + \frac{h}{n_1} . \quad (12)$$

So when

$$R = (n_1 - 1)(\frac{S_1}{n} + \frac{h}{n_1}) , \quad (13)$$

we can get the maximum W_2,

$$W_2 = \frac{f\lambda}{n_1 \pi W_1} . \quad (14)$$

Similarly, $W_1 \propto f$, $W_2 \propto 1/W_1$, therefore a thicker substrate and polymer material, a lower index and a smaller beam waist before collimation can ensure a smaller divergence angle. As a matter of fact, the choice for suitable polymer material is limited, and so does its index. Thus, we will not give a consideration on the change of index in the following part.

In this part, the simulation results for common InGaAs/GaAs VCSELs[9,10] with integrated microlens with the help of ZEMAX are given. Parameters needed are listed in Tab.1.

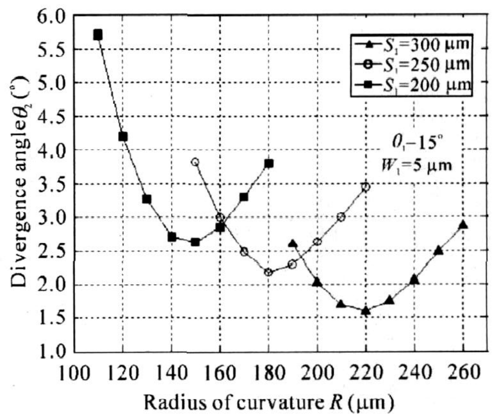
Tab.1 Relevant parameters

Parameter	Value
Wavelength in vacuum λ	0.98 μm
Divergence angle ($1/e^2$) θ_1	15°
Diameter of emitting aperture W	50 μm
Period of the array L	100 μm
Index of GaAs n	3.51
Index of SU-8 n_1	1.59

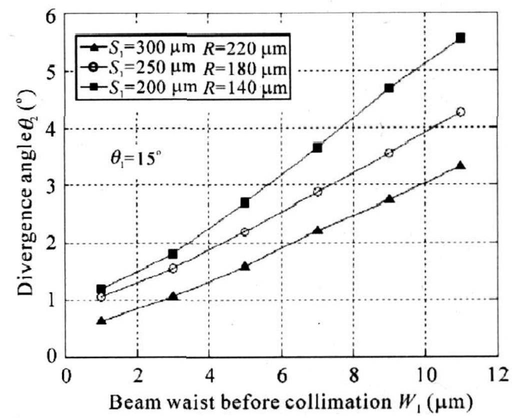
Fig.3 is the situation when the microlens is on the substrate directly.

Fig.3(a) shows the relationship between the divergence angle after collimation and the radius of curvature of the microlens for different thicknesses of the substrate. We can see that for any thickness, there is a corresponding optimal R which makes θ_2 minimum, and the thicker the substrate is, the smaller θ_2 will be. Meanwhile, for R within several tens of microns near the optimized value, θ_2 remains close to the minimum, and the thicker the substrate is, the less the influence of R will be, which means a looser tolerance for manufacture process. On the other hand, for the three situations, the calculated values of R by Eq.(8) are 143 μm, 178.8 μm and 214.5 μm, respectively, which agree with the simulated results.

Fig.3(b) shows the relationship between θ_2 and W_1 for



(a) Relationship between divergence angle and radius of curvature for different thicknesses of substrate



(b) Relationship between divergence angle and beam waist for different thicknesses of substrate with corresponding best radius of curvature

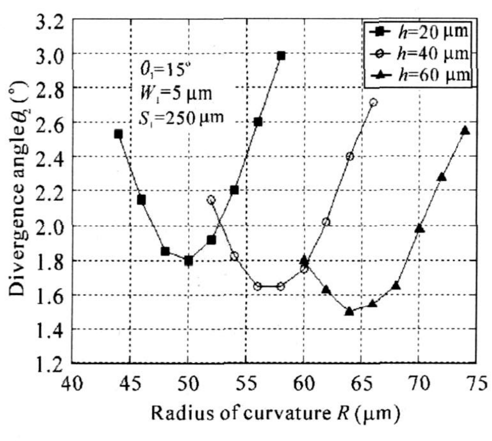
Fig.3 Situation for the microlens on the substrate directly

different thicknesses of the substrate and the corresponding optimal radii of curvature. We can see that for all the three situations, q_2 gets larger linearly with W_1, that is, $q_2 \propto W_1$, which is in accordance with the result $W_2 \propto 1/W_1$ above. For the device with the substrate thickness of 300 μm and beam waist of 2 μm, q_2 is able to be smaller than 1°; for that with the beam waist of 10 μm, q_2 is able to be reduced to lower than 3°, which indicates the possibility for an enhancement of beam power compared with devices with the beam waist of 2-4 μm for a small divergence angle.

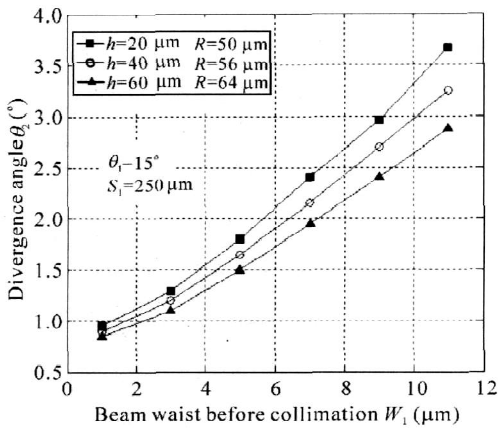
Fig.4 is the situation when the microlens is on SU-8. Fig.4 (a) shows the relationship between the divergence angle after collimation and the radius of curvature of the microlens for the same thickness of the substrate with different thicknesses of SU-8. Similarly, for any thickness of SU-8, there is a corresponding optimal R which makes q_2 minimum, and the thicker the SU-8 is, the smaller q_2 will be. However, for R within several tens of microns near the optimized value, q_2 will no longer remain close to the minimum but a rather huge difference, and the thinner the SU-8 is, the greater the difference will be, which means a more tight tolerance for manufacture process. For the three situations, the calculated values of R by Eq.(13) are 49.4 μm, 56.9 μm and 64.3 μm, respectively, which also agree with the simulated results.

Fig.4(b) shows the relationship between q_2 and W_1 for the same thickness of the substrate but different thicknesses of SU-8 with the corresponding optimal radius of curvature. Similarly, for the devices with the beam waists of 2 μm and 10 μm, the minimum q_2 values are able to get lower than 1° and 3°, respectively.

Based on the above analysis, we believe that it is reasonable to increase the thicknesses of the substrate and the polymer material and to reduce the diameter of the beam waist so that we can get an even smaller q_2. Admittedly, these measures will affect cooling, efficiency and power of the device. However, the results also show that a relatively small divergence angle can be obtained for beam waist as large as 10 μm, which makes it possible for devices to have both high power and small divergence angle.



(a) Relationship between divergence angle and radius of curvature for the same thickness of substrate but different thicknesses of SU-8



(b) Relationship between divergence angle and beam waist for the same thickness of substrate but different thicknesses of substrate with corresponding best radius of curvature

Fig.4 Situation for the microlens on SU-8

The method of designing the integrated microlens for collimation of VCSEL array based on the theory of transfer matrix is presented. Furthermore, the relationships between the radius of curvature, beam waist and the divergence angle for devices with different thicknesses of the substrate and SU-8 with the help of ZEMAX are got. The results show that for the device with the divergence angle ($1/e^2$) of 15° and beam waist of 2 μm, the divergence angle can be reduced to lower than 1° ; for that with beam waist of 10 μm, the divergence angle can be reduced to lower than 3°, and thus the higher power with small divergence angle can be realized. The conclusion that increasing the thicknesses of the substrate and the polymer material and reducing the diameter of the oxidized layer will bring looser tolerance for manufacture process is also obtained, which is an important guidance for experiment research.

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