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Enhancement of the far-field output power and the properties of the very-small-aperture lasers

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ABSTRACT We report on a VSAL structure fabricated by a 650 nm edge emitting laser diode with an Au-coated facet and an aperture size of 250 × 500 nm. The far field output power can maintain at 1 mW and the power density is 7.5 mW/μm^2. Some properties of the VSAL including the threshold current change, the red-shift of the spectral position, and the strong relative-intensity-noise are presented. The physical mechanisms responsible for these phenomena are also discussed, which may contribute to the understanding and application of the potential device for near-field optics.

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1 Introduction

It has been of interest to develop a near-field optical source to deliver considerable optical power to a medium through a highly confined optical aperture. In 1999, Afshin Partovi et al. developed a light source called the very-mall-aperture-laser (VSAL) in which a small aperture was fabricated with a metal-coated facet for a 980 nm laser diode [1]. In 2001, Fang Chen et al. achieved VSALs of commercial edge emitting lasers with the wavelength ranging from 635–655 nm [2]. However, subwavelength metallic apertures suffer from very low throughput. Consequently, the output power of such lasers is too low to be applied in optical near field storage. In 2003, some reported theoretical and experimental evidences show that certain C-shaped apertures can enhance the output power [3, 4]. With the recent technological refinements and advances, metal can be structured on the nanometer scale and the surface plasmon properties can be controlled to modulate the light through the aperture [5, 6]. In this way, the output power through the aperture of the VSALs can also be enhanced.

In this paper, we report on a VSAL structure of the 650 nm commercial edge emitting laser diode in which a 250 nm × 500 nm aperture was fabricated with an Au-coated facet. Our results indicate that the far-field output power can maintain at 1 mW and the power per unit emission area is about 7.5 mW/μm^2. We calculate the Poynting vector around the aperture by Finite Difference Time Domain (FDTD) method. Some properties of the VSALs such as the threshold current change, the red-shift of the spectral position, and the large relative-intensity-noise (RIN) are observed. The physical mechanisms responsible for these phenomena are also discussed.

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2 High output power VSAL

The basic fabrication process involves the following steps:

1. Deposition of SiO_2 and SiN_x coating films on the front facet of a commercial diode. This step is to protect the front facet from breaking in the following step 2 or step 3, which will certainly deteriorate the performance of the laser diode.
2. Au film deposition. This step is to cover the front facet with Au to prevent the light from emitting.
3. Aperture formation by focused ion beam (FIB) system. This is accomplished with an FIB with the resolution of 7 nm. Figure 1d shows the scanning electron microscopy (SEM) image of the fabricated 250 nm × 500 nm aperture. In addition, some special steps can be introduced to improve the fabrication yield [7].

The measurements demonstrate that the far-field output power of the device maintains at 1 mW and the power per unit emission area is about 7.5 mW/μm^2. Figure 1 shows the Output Power-Drive Current (P-I) curve and the Voltage-Drive Current (V-I) curve of the laser diode without Au-coated facet (a), the laser diode with Au-coated facet (b) and Fig. 1c the VSAL (c), respectively. It is obvious that the threshold current of the device decreases from 30 mA to about 15 mA and the output power is increased up to 1 mW when the current is 45 mA. Considering such a large output power, we believe that this type of VSAL can be used in the near-field optical data storage field. As shown in Fig. 2, we captured the near-field distribution from the small aperture using an optical microscope with magnification capacity of

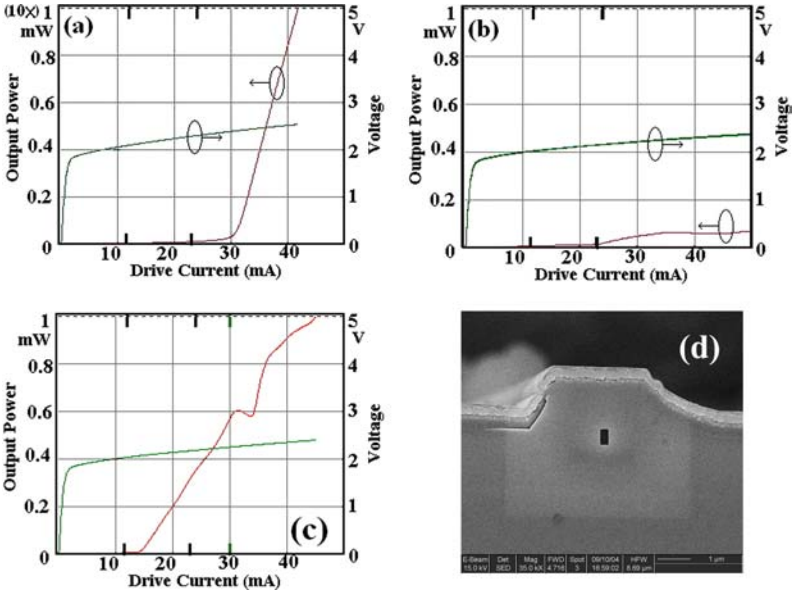

FIGURE 1 **a** The output power-drive current (P-I) curve and junction voltage-drive current (V-I) curve of 650 nm laser diode without Au-coated facet; **b** P-I and V-I curves of 650 nm laser diode with Au-coated facet; **c** P-I and V-I curves of the VSAL; **d** SEM image of the metallized front facet of the VSAL with a 250 nm × 500 nm aperture

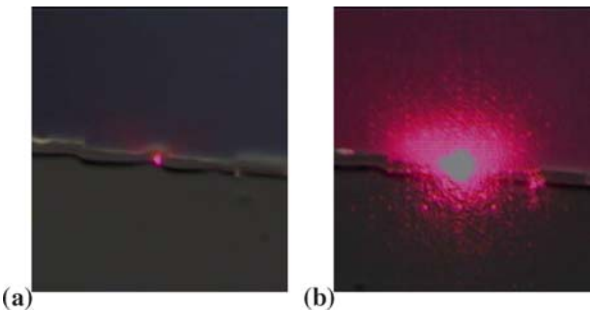

FIGURE 2 Near-field distribution of a VSAL which is tested at 5 mA **a** and 25 mA **b**

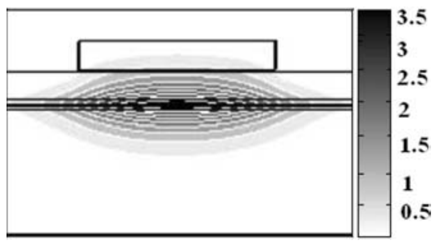

FIGURE 3 Near-field distribution calculated by semi-vector finite difference method

1000. Figure 2 shows the captured picture when the current is 5 mA and 25 mA, respectively. From the photo, it can be seen that the light dose emit from the aperture rather than other positions.

However, considering the complex structure on the front facet of the laser diode, one sees that the reliability of the VSAL is unstable due to thermal or optical deterioration. Because of the light absorption of the Au film, the temperature of the front facet may increase being harmful to the reliability [8]. Therefore, we propose to use stable diodes that can stand at high temperature during the fabrication of VSALs.

3 Simulation of the near-field distribution

The near-field distribution of the uncoated laser diode is calculated by the semi-vector Finite Difference Method and the results are shown in Fig. 3. The calculated power in the center of the near-field distribution of the 250 nm × 500 nm area is 11.832% of the whole power. Unfortunately, however, according to the traditional theory [9], if the diameter of the aperture is smaller than $\lambda/2$, the aperture does not support the propagating modes and the tunneling thus becomes a necessary part of the transmission mechanism. As a result, the far-field output power through the small aperture should be weak. Since one dimension of the device's aperture is smaller than $\lambda/2$ (only 250 nm), the power transmits through the aperture should be much smaller than 11.832%. As can be seen in Fig. 1a, we find that the output power of an uncoated laser diode is 8.5 mW when the current is 40 mA while, as shown in Fig. 1c, the net output power through the aperture is about 0.9 mW corresponding to 10.6% of the input power for the same current of 40 mA. It can be seen from Fig. 3 that the far field transmission rate is only a little smaller than the calculated result. Namely, about 90% of the light which hits the aperture can emit from the aperture. In this regard, we suspect that the transmission rate of our devices' aperture is ultra-high. In the following sections, we show the simulation results of the near-field distribution around the aperture.

4 Transmission through the aperture on the metal film

It is believed that when the lateral dimension of subwavelength apertures is smaller than half the wavelength, light cannot propagate though the hole and transmission is typically very weak. The first result is stated by Bethe in 1944 by analyzing the transmission through a small hole in an infinitely thin perfectly metal screen [9]. However, a real subwavelength aperture on the real metal is very different because the thickness and the finite conductivity of the metal has significant consequences which are far from being well understood [10].

Figure 4 shows the FDTD simulation model and the simulation results in the y-z plane [11]. In the calculation, a $250 \times 500\,\text{nm}^2$ aperture on a perfect conducting film with thickness of 100 nm is used and an y-polarized (E_y) incident light $\lambda = 650\,\text{nm}$ along the Z direction in the air is then added. We find that the small aperture can be regarded as a topologic defect on the metal surface which may excite surface plasmons (SPs) and enhance the near-field light around the aperture. However, the enhancement due to the SPs is weak and only the light around the aperture can emit from the small hole. Although the near-field distribution is enhanced, the far-field distribution may not be enhanced because the SPs are evanescent waves which cannot propagate from the surface to the far-field. Considering the calculated far field transmission rate is much smaller than 90% (the ratio of the energies hit the aperture and through the aperture), we believe that some other main factors lead to the high far-field output power of the VSAL.

5 Strong optical feedback caused by the Au film

In this section, we discuss the main factor contributing to the high output power of the VSAL in the far-filed. It is well known that the threshold current will be reduced due to the strong optical feedback and correspondingly the output power will increase when the drive current is constant [12]. The performance characteristics of the laser diodes with or without Au film are shown in Fig. 5. Figure 5a and c depict the P-I curves measured from the back facet of an uncoated laser diode and from its front facet, respectively; Fig. 5b shows the P-I curve from the back facet of the laser diode with an Au-coated front facet. As can be seen, the threshold current decreases from 24 mA in Fig. 5a to 18 mA in Fig. 5b. When the output power is 10 mW, the drive current is 30 mA for the uncoated laser diode while that of the laser diode with Au-coated front facet is only 21 mA under which the uncoated laser diode cannot emit. On the other hand, when the drive current is 23 mA, the corresponding output power of the coated laser diode is about 22 mW which is larger than 10 mW for the uncoated laser diode. Thus, we can conclude that, when the output power of the VSAL reaches 1 mW at the current of 45 mA, the internal power is much larger than that the uncoated laser diode can emit at the current of 45 mA. Namely, the transmission rate through the aperture may not be ultra-high, the high output power arise from that the power of the laser diode is enhanced at constant drive current by the strong optical feedback. If some light can emit from the aperture on the front facet, the optical feedback will be weakened. In such a way, the threshold current should be increased correspondingly. Figure 5d shows the P-I curve of the same laser diode as shown in Fig. 5b but after aperture is formed. It is clear that the threshold current is larger than that in Fig. 5b.

In this section, we have taken the Au film as an external optical feedback source and have analyzed the performance of the laser diode. Alternatively, we can also regard the Au film and the front facet of the uncoated laser diode as a whole. Similar results can then be obtained if the performance of the laser diode is analyzed considering the different average reflectivity of the front facet [8].

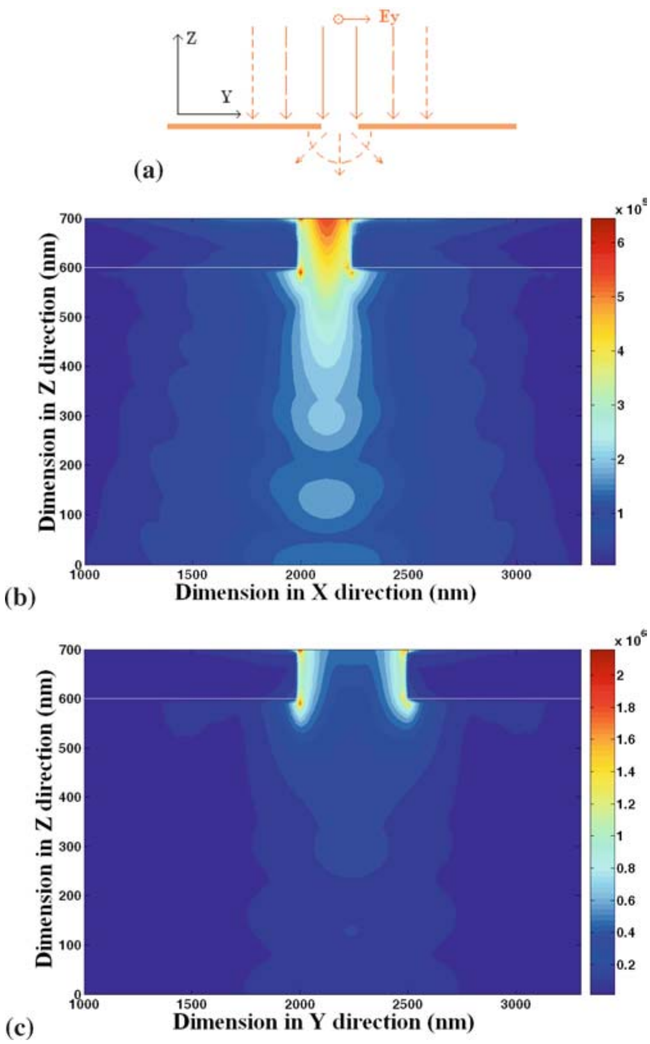

FIGURE 4 **a** FDTD simulation model; **b** E field distribution simulation result in X-Z plane through the center of the aperture; **c** E field distribution simulation result in Y-Z plane through the center of the aperture

6 Strong RIN of VSALs

Because of the strong optical feedback, besides the threshold current change, RIN is also affected. As demonstrated previously, the RIN is increased with increasing the optical feedback [11]. Figure 6 shows the results of the RIN of the VSAL tested at different drive current. As can be seen, the RIN of the VSAL is larger than that of the uncoated laser diode at low drive current while the uncoated laser diode cannot emit at such a low drive current (less than 24 mA).

7 Red-shift of the VSALs' spectral position

Since the front facet of the VSAL is covered with a thin metal film (about 100 nm thick), much light will be absorbed by the metal film in the visible region. If the absorbed energy accumulates in the metal film, the temperature is thus expected to be high. Consequently, the Au film will become a heat source near the front facet; if the temperature

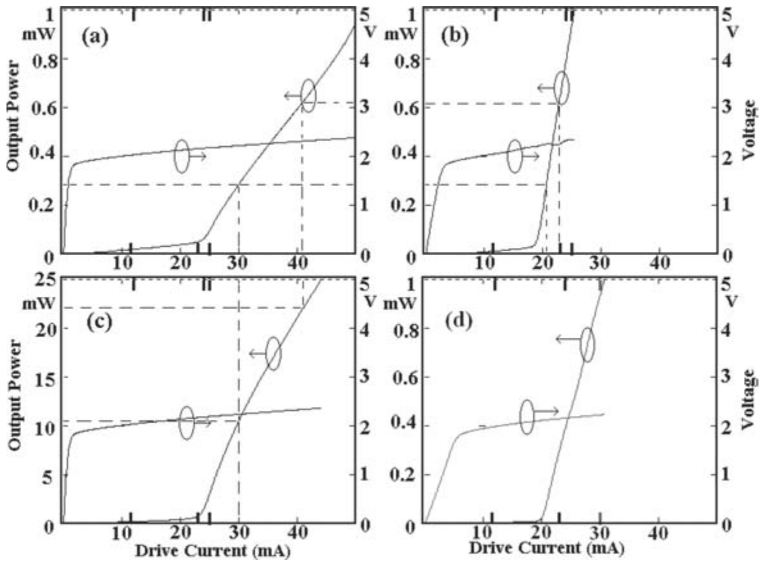

FIGURE 5 **a** P-I curve and V-I curve from the back facet of a 650 nm laser diode without Au-coated facet, **b** P-I and V-I curves from back facet of a 650 nm laser diode with Au-coated facet, **c** P-I and V-I curves from the front facet of a 650 nm laser diode without Au-coated facet, **d** P-I and V-I curves from the back facet of a VSAL with a 250 nm × 500 nm aperture. As we can see, the threshold current in **b** is lower than **a**, while the threshold current in **d** is larger than that in **b**

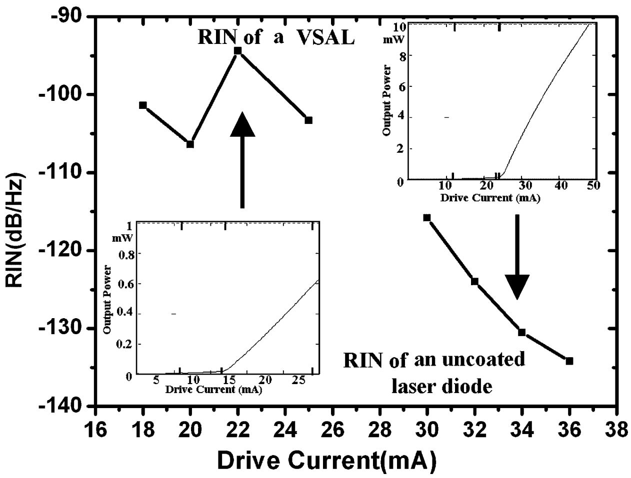

FIGURE 6 RIN contrast between a VSAL and an uncoated laser diode. *Insets* are P-I curves of the VSAL and the uncoated laser diode

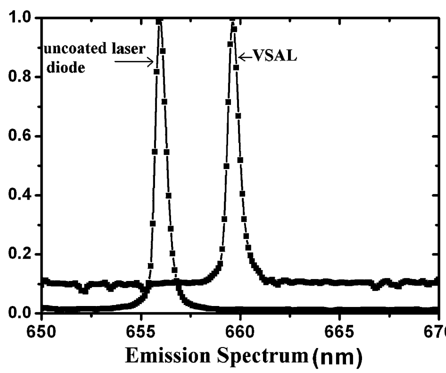

FIGURE 7 Emission spectrum contrast between a VSAL and an uncoated laser diode. The spectral position of the VSAL is about 660 nm, which is larger than that of the uncoated laser diode (about 657 nm)

inside the laser diode is increased, the band gap of the active layer will shrink resulting in a red-shift of the emission spectrum. Figure 7 shows the spectrum of the VSAL and the emission wavelength is larger than that of the uncoated laser diode.

8 Conclusion

In summary, we have developed a high output power VSAL and revealed the physical mechanism underlying the observed high output power. Although the near-field power may be enhanced by SPs, the transmission rate of the single aperture in the far-field is not enhanced obviously. Optical feedback is the main factor leading to the high output power of the VSALs at a relatively low drive current. Some characteristics including the threshold current change, the red-shift of the spectral position, and the high RIN are tested. Our work may contribute to the understanding and application of the potential device for near-field optics.

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