Near-field fiber tip to handle high input power more than 150 mW

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A high-power near-field fiber tip is proposed and demonstrated. This high-power tip can handle an optical power of greater than 150 mW injected into the fiber core, higher than any previous tip. The tip has a unique, thick, heat-conducting metal layer deposited by an electroplating process. The subwavelength aperture of the tip is fabricated by the controlled lapping of the end face with in situ optical monitoring. We also demonstrate using this tip to record on phase change and photoresist media. © 2000 American Institute of Physics. [S0003-6951(00)03343-X]

The near-field scanning optical microscope (NSOM) has been investigated as a tool for photolithography on submicron scales1,2 and for high-density optical recording on various media, such as magneto-optical, phase change, and organic materials, because its metal-coated tip can give an optical spot smaller than the far-field diffraction limit.3–5 Even though another near-field technology using solid immersion lenses (SIL) has been studied recently,6 as far as the recording density goes, the NSOM technology is preferable because the diffraction limit is unavoidable with SILs. However, the writing and reading speeds of NSOMs that have been achieved so far is too low to be used for practical storage devices. The low speed is mainly due to two factors. The first is that the moving speed of the tip is too slow. In past experiments, the scanning has been performed by piezoelectric actuators for which the scanning speed has been, at most, 100 μm/s, due to the necessary control of the distance between the tip and the sample to within 10 nm. The second is the poor transmission efficiency, i.e., the low optical power emitting from the tip, which means a long time is required to record a mark. A dominant fraction of the light energy passed through a metal-coated fiber tip is absorbed by the metal cladding near the tiny apex. Therefore, the high input power readily overheats and destroys the thin metal coating around the aperture. This imposes the upper limit to the input power of 15 mW in pulses or 2–3 mW in cw, which is much lower than is currently available from lasers.

The problem of the slow scanning speed can be solved by using the air-bearing sliders of a low-fly height developed for hard disk drives (HDDs) or piezoelectric servoactuators attached to an air-suspended pad by which the gap error can be constrained within 10 nm.7 Therefore, the low optical power has become the more serious bottleneck in preventing high-speed recording and also causes low signal-to-noise ratios due to the shot noise of photodiodes. In this letter, we propose and demonstrate a tip structure suitable for high-power near-field applications. The fabrication and evaluation process of the tip are presented. Recording experiments on phase change and photoresist media are demonstrated using this tip.

Efforts to enhance the emission from a near-field optical tip have been focused on optimizing taper profiles of the tip. Careful tailoring of the taper structure has greatly improved the transmission efficiency of the tip, but the efficiency still remains less than the order of 1.0% with an aperture diameter of ~0.1 μm.8,9 Therefore, if one wants to transmit more optical power, one has to increase the input optical power. Our approach is to improve the thermal characteristics of near-field tips by introducing an efficient heat-conducting layer in the form of a thick metal coating.

The fabrication process of our tips is schematically summarized in Fig. 1. First, bare optical fibers are tapered with a pipette puller, Sutter P2000 [Fig. 1(a)]. The parameters of the pulling are chosen so as to produce a high-throughput tip, which has a short taper length of about 150 μm and a parabolic shape similar to that reported in Ref. 7. The diameter and taper angle at the extreme end are about 100 nm and 30°–40°, respectively. Second, Al or Au is sputter deposited to form a 0.5-μm-thick reflecting layer on the tapered fiber to confine the light in the taper [Fig. 1(b)]. Third, the heat-conducting layer is electroplated in Ni solution [Fig. 1(c)]. The metal-coated tapers are dipped into the Ni solution at 55 °C and 10 mA of electrical current is supplied for 12 min at a bias of 2.5 V. Then, a 150-μm-thick Ni plating is hemispherically formed at the end of the tip as well as along the side. Finally, the lapping of the electroplated taper is performed [Fig. 1(d)]. A piece of diamond lapping tape, having an average grain size of 0.5 μm, is attached to a glass disk which simultaneously rotates and translates, as shown in Fig. 1(e). The electroplated taper is glued at the end of a plastic suspension by which a pressing force of 1.5 g is applied to the tip. The rotation speed of the spindle motor and the stroke of the voice coil motor are set to be 600 rpm and 2.5 cm, respectively. In this condition, the lapping speed, after being high at the beginning, becomes about 1 μm/min and the aperture is open in 1 h.

The aperture diameter is controlled by in situ monitoring the emission from the laser-coupled tip using a wide-area power meter located below the disk. The opening of the ap-
Aperture is identified as an abrupt increase of the monitored optical power. The final aperture diameter is inspected with a scanning electron microscope (SEM). Once the relation between the monitor power and the real aperture size is set, we are able to fabricate an aperture having a predetermined diameter with high accuracy. Experimentally, the lapping is terminated at a preset monitored power level by lifting the suspension with a computer-controlled solenoid actuator. Apertures of various diameters obtained in the experiment are displayed in Fig. 2.

The power-handling capability of the high-power near-field tip with an Al reflection layer and aperture size of 300 nm was examined first. Our high-power tip remained undamaged and acquired an output power of 0.46 mW with a 150 mW input of a cw Ar laser tuned to a wavelength of 514 nm. This allowed input power to the near-field tip of at least 50 times higher than those of conventional thinly coated tips. The temperature of the tip was also measured with a spot thermometer (Minolta TR0506C). When the light power in the fiber core changes from 0 to 150 mW, the temperature of the side of the tip increases from 20 to 112 °C and the light output increases linearly up to 0.46 mW.

Our lapping process also provides an opportunity to investigate the light propagation in the taper. In Fig. 3, the transmission efficiency is explored as a function of the aperture diameter at two different wavelengths. For wavelengths of 635 and 458 nm, two kinds of tips are made of fibers that are single mode at the respective wavelength. The reflecting layer is Au in the 635 nm case and Al in the 458 nm case. The pulling condition that is optimized for the tip in the 635 nm case is used identically for both tips, so the taper shape is not optimal for the 458 nm case.

As shown in Fig. 3(a), the transmission efficiency in the 635 nm case decreases almost linearly as the aperture diameter decreases from 0.5 μm to 150 nm. In particular, the transmission efficiency through the 100 nm aperture is measured to be 0.04%, which is relatively high, implying an optimized taper shape at this wavelength. On the other hand, the normalized intensity increases slightly and shows a maximum of 2.0 mW/μm² when the aperture diameter is 230 nm. Here, the normalized intensity is the intensity at the aperture obtained with 1 mW input. However, the intensity decreases abruptly when the aperture becomes smaller than 230 nm. This reflects the fact that there exists a transition diameter of the lowest mode in a metallic cylindrical waveguide, which is about λ/2n. Here, λ is the wavelength and n is the index of the core. The light cannot propagate efficiently in a region smaller than the transition diameter since the mode changes from propagating to decaying. The sensitivity of the current phase change or magneto-optical media requires a writing intensity of 10 mW/μm², which is easily achievable with our 150 nm aperture by putting 20 mW into the fiber core, as can be seen in Fig. 3(a).

With the tip for λ = 458 nm, the transmission efficiency of the 100 nm aperture is found to be only 0.01%, which is...
even worse than that in the case of 635 nm. This unexpectedly low efficiency is attributed to the nonoptimized taper shape. Actually, the light leaks out from the middle region before reaching the final apex in the bare fiber tip. This could be understood if we apply a wavelength unit to consider the probe size. The probe of \( \lambda = 458 \) nm is larger than that of \( \lambda = 635 \) nm. Since the number of excited modes in a cylindrical waveguide increases as the diameter is larger and only the fundamental mode reaches the end to contribute to a throughput, a probe of a large taper diameter cannot have good transmission. Therefore, it is preferable to make probes from a thin fiber or use other tip-fabrication methods to get an optimum taper for \( \lambda = 458 \) nm. Anyway, the normalized intensity shows a maximum of about 0.25 mW/\( \mu m^2 \) at a diameter of 160 nm, corresponding to the transition diameter for this wavelength. If we consider the threshold energy of 1 nJ/\( \mu m^2 \) of the current positive photoresist, a writing speed of 1.3 m/s or 4.3 MHz write carrier frequency can be readily achieved by the 0.2 mW optical spot of the 150 nm aperture tip coupled with a 40 mW laser beam.

The recording experiments on the phase change medium and photoresist are performed with the high-power near-field tip. For the first, we use the phase change medium optimized at the wavelength of 650 nm. The 12 mW light pulse of 60 ns duration from a NA 0.6 objective lens makes a mark of 0.5 \( \mu m \) length on the medium. For the convenience of examination with an optical microscope, the 0.5 \( \mu m \) aperture tip coupled with the 635 nm diode laser is employed to record marks. The choice of this large aperture does not influence the experiment to check the optical intensity for aperture sizes larger than 0.2 \( \mu m \), since the intensity stays almost constant. A small region of the initially crystalline state is melted by the intense light pulse and cooled down abruptly to be an amorphous mark of higher optical transmission. Figure 4(a) shows the 125 ns light pulse from the tip monitored by a high-speed detector and Fig. 4(b) shows the change of the transmitted light power that is monitored by the power meter under the sample. When the write and read power are set to be 4 and 0.35 mW, respectively, the transmitting light power changes from 53 to 70 \( \mu W \), as shown in Fig. 4(b), and unambiguous 0.7 \( \mu m \) marks are recorded.

To test the writing capability on the photoresist, the light of a 458 nm Ar laser is coupled into the 0.5 \( \mu m \) aperture tip that is mounted onto a HDD slider. A 120-nm-thick positive photoresist and a lubricant are spin coated on a glass disk. At a scanning speed of 1.2 m/s, pits of 1 \( \mu m \) width are created with 2 mW output power from the tip, as shown in Fig. 5. The enlargement of the pits is thought to be caused by the large gap between the tip and sample, originating from the tip mounting tilting during the glue hardening. This problem can be overcome by changing the assembling process to one in which the bending of the bottomside of the slider is added after the glue hardening. Another possible reason is the effect of surface plasmons excited near the aperture.\(^1\) In any case, we show that this tip has an optical power suitable for the optical disk mastering at a practical exposure speed.

In summary, we propose and demonstrate a high-power near-field tip having a unique heat-conducting layer for high-power near-field applications such as optical recording and photolithography. The 150-\( \mu m \)-thick heat-conducting layer electroplated on a metal-coated fiber taper greatly enhances the maximum input power to the tip by more than 50 times that of thinly coated fiber tips. The thermal analysis shows that the temperature of the tip is maintained below 112 °C even when the input power increases up to 150 mW. The presence of the transition diameters in the taper is observed during the throughput measurements as a function of aperture size, which are realized by the controllability of the aperture size of the tip. The recording experiments demonstrate that the light power of this tip can be high enough to record a mark on phase change media in submicroseconds and photoresist at a practical exposure speed.

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