

Generation of Compact Near-Field Energy for Optical Recording: Transducer Efficiency and Signal Detection

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A new theory of illumination is derived for near-field optical transducers, in which transmitted power is related to total power in the illuminating laser beam. Several transducers are compared, including simple holes in metallic films, a dielectric probe and solid immersion lens combination, and plasmon-enhanced holes. The ratio of transmitted power to incident power is a function of the illumination numerical aperture, due to the angular selectivity of the transducers. Also, a simplified collection theory is reviewed, which reveals that, when transducers are used for the collection of data signals in optical storage applications, a combination of the transducer and a solid immersion lens provides a large angular collection range, and hence a good contrast signal. [DOI: 10.1143/JJAP.42.1095]

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1. Introduction

The never-ending quest for higher capacity optical disks leads engineers and scientists to consider producing the smallest spot size possible, because spot size is directly related to the smallest mark that can be written and the highest frequency data that can be read. Philosophically, an arbitrarily small spot size can be obtained by simply forcing photons through a small enough aperture. In fact, the first demonstration of smaller-than-diffraction-limited spots used for optical recording used a 50 nm diameter aperture on the end of an elongated fiber probe was used.¹⁾ This demonstration illustrated three engineering trade-offs associated with using ultrasmall spots for data storage

- (1) *The probe that produces compact energy must be in proximity to the data layer. These devices are called near-field transducers (or near-field probes),* because separation distances are less than the decay length of the emitted energy. This restriction can lead to the need for complicated mechanical servos to control probe-to-disk separation, as well as serious contamination issues. In Betzig's experiment, the probe-to-sample separation is about 10 nm. Recent experiments involve air-bearing sliders to maintain a small separation, which are similar to sliders used in the hard-disk industry.²⁾
- (2) *Near-field probes suffer from poor light throughput.* Typically, much energy is lost in spot generation due to absorption in metals used to define the aperture. Rates for writing and reading data are seriously limited. In Betzig's experiment, approximately one photon is transmitted through the transducer to the sample for every 10^5 photons launched into the fiber.
- (3) *Near-field probes have difficulty reading data in reflection.* This complication is partially due to low throughput, but a more fundamental limitation is the restricted collection of light energy inherent in most probe designs. In Betzig's experiment, the data rate is limited to about 10 kHz. Optical geometries associated with reading in transmission are difficult to produce in consumer products, so the preferred geometry is to read in reflection.

Several variations of near-field transducers include a simple hole in a conductive screen, plasmon-enhanced holes,³⁾ antennae structures,⁴⁾ superresolution near-field structure (super-RENS) media,⁵⁾ very small aperture lasers (VSALs),⁶⁾ solid-immersion lenses (SILs),⁷⁾ and combined-aperture SILs (APSILs).⁸⁾ Some of these techniques have been reviewed in recent articles.^{9,10)}

With respect to items (2) and (3) above, results of recent experiments suggest that extremely high throughput is achieved when a dielectric-probe transducer is combined with a SIL.⁸⁾ Only 50% light loss is observed in reflection for a transducer that produces a 200 nm full-width-at- $1/e^2$ (FW1/ e^2)-diameter spot, which is several orders of magnitude higher than in other transducer designs. One objective of this study is to understand, on a conceptual level, why the dielectric APSIL transducer exhibits such high throughput. The analysis reported here includes the development of a theory of illumination, which combines the properties of both the illumination beam and transducer angular sensitivity to predict a power ratio T , where

$$T = \frac{P'}{P} = \frac{\text{power delivered to the surface of interest}}{\text{total power in the illuminating beam}} \quad (1.1)$$

Illumination theory is also applied to several other transducers for comparison. A second objective of this study is to review the theory of detection as applied to near-field transducers. For some transducers, detection is not a significant issue, like those used for hybrid recording,¹¹⁾ but detection is significant in applications where the transducer functions as part of the collection path.

This paper is divided into several sections. First, a linear superposition model is proposed based on the properties of ideal metallic holes. Both theoretical and finite-difference-time-domain (FDTD) tools are used to illustrate angular selectivity of transducers and the power ratio for plane-wave illumination. Next, a theory of illumination is introduced. The power ratio is calculated based on a simple Gaussian model of angular sensitivity and focused illumination, followed by a method of estimating angular sensitivity of actual transducers. Several transducers are compared as a function of focused-illumination numerical aperture (NA). A previously described theory of collection⁹⁾ is then applied to several transducers. A short summary is presented with

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