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A volume holographic optical element for optical coupling to single-mode fibers

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ABSTRACT

We propose and demonstrate a volume holographic optical element (VHOE) for signal-mode fiber coupling and the sending of conjugate waves of reference light for the construction of holographic elements. Given the inherent Bragg conditions of the VHOE, the angular tolerances of the conjugate reading light in both the horizontal and vertical directions are studied under different conditions.

1. Introduction

Volume holography is desirable for various applications including data storage and novel optical elements because it possesses the characteristics of high storage capacity, high selectivity in the spatial and temporal domains and high diffraction efficiency [1–3]. Optical elements based on volume holography, the so-called volume holographic optical elements (VHOE), provide more design freedom and better optical parallelism [4–17]. In comparison with a conventional diffractive optical element (DOE), with the VHOE, it is easier to perform high efficiency diffraction, backward diffraction and complex functions. Though a suitable volume holographic recording material is not yet available, VHOE has become important in the design of novel optical elements. A fiber-to-fiber coupling scheme that uses self-conjugate waves has already been proposed [18–19]. We propose a VHOE design for the optical coupling of single-mode fibers with the capacity of sending a conjugate reading light. To design a VHOE with high selectivity, both spatial and temporal selectivity are important. Thus, theoretical calculation of the coupling tolerance in both horizontal and vertical directions is done, and the corresponding experimental results demonstrated.

2. Principles and simulation

A schematic drawing of the single-mode fiber coupling scheme is shown in Fig. 1. The light from a laser is coupled into a single-mode fiber through a VHOE. The VHOE is made by recording the interference fringe formed by the reference light, which is formed by a convergent spherical wave directed toward the laser, and a signal which is a divergent spherical wave emitted from the end of the single-mode fiber. During the coupling process, the divergent spherical wave emitted by a laser serves as the reading light, which is a phase conjugate of the reference wave used in the writing process. According to the Bragg condition, the diffracted light should be the phase conjugate of the signal, and will self couple into the single-mode fiber, as shown in Fig. 1b. The reading light can be coupled into the fiber through the VHOE.

In a single-mode fiber, the coupling efficiency is very sensitive to spatial misalignment. We now analyze the coupling tolerance in different directions. The VHOE is a volume hologram which records the interference fringes formed by signal S and a reference light R. The fringes can be expressed as

$$t_j \propto |Se^{i\phi_S} + Re^{i\phi_R}|^2, \tag{1}$$

where ϕ_S and ϕ_R indicate the phase of the signal and the reference wave, respectively. Based on the VOHIL model for coupling conditions, i.e., the volume hologram is an integrator of light emitted from elementary light sources [20], the diffraction can be written as

$$D_A \propto \int \left[(|S|^2+|R|^2)P + PS^*Re^{i\{\phi_P-\phi_R+\phi_S\}} + PSR^*e^{i\{\phi_P-\phi_R+\phi_S\}}\right] e^{i\vec{k}d(\vec{r}_2-\vec{r}_1)}d\vec{r}_1, \tag{2}$$

where P and ϕ_P are the amplitude and the phase of the probe beam; $\vec{r}_1$ is the vector for the diffracted center in the recording medium; and $\vec{r}_2$ is the vector along the diffracted light. From Eq. (2), it can be seen that, when the reading light is the same as the reference light, the diffracted light is an exact reconstruction of the signal. However, if the reading light is different from the reference light,

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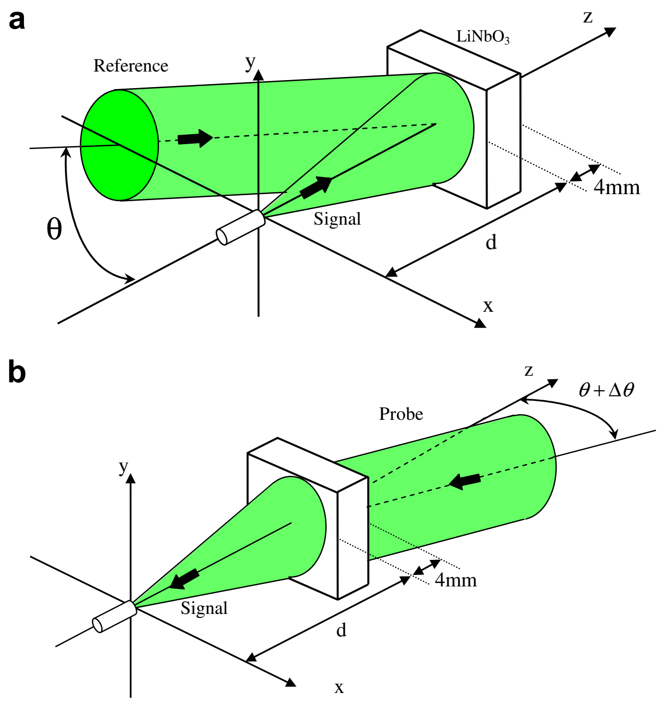

Fig. 1. Schematic diagram of a VHOE based fiber coupling where: (a) represents the writing condition; (b) the reading condition, where the reading light is the phase conjugate of the reference used to construct the VHOE.

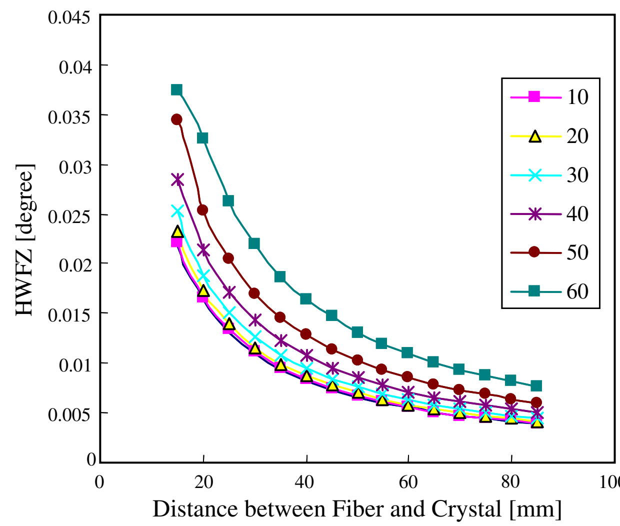

Fig. 2. Horizontal-angular diffraction tolerance of the VHOE at different distances and angles of reference light from 10° to 60°.

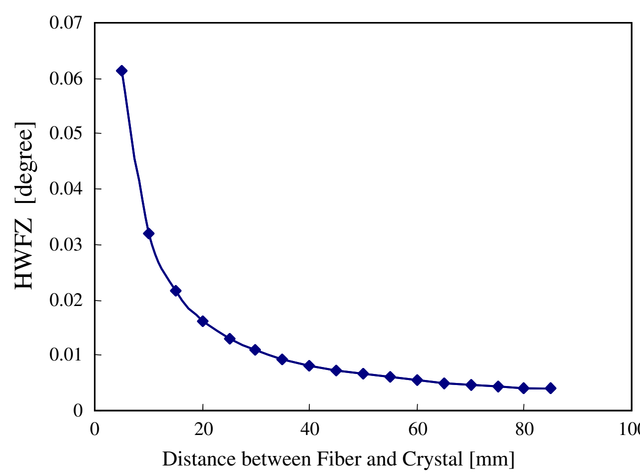

Fig. 3. Vertical-angular diffraction tolerance of the VHOE at different distances and angles of reference light from 10° to 60°; where the tolerance is almost identical at different angles.

either due to defocusing or tilting, or both, the intensity of the diffracted light decreases dramatically owing to Bragg mismatching.

In the simulation, the wavelength of the light source is 532 nm, and the dimensions of the recording medium are 10 mm × 10 mm × 4 mm (*x*,*y*,*z*). The reference is a plane wave, i.e., the light source is at infinity, with an incident angle of θ with respect to the normal angle of the crystal. The signal is a divergent spherical wave with a numerical aperture (NA) of 0.056, and the point source of the spherical wave is located at the entrance face of the coupled single-mode fiber, at a distance *d* from the incidence surface of the VHOE, along the normal surface. In the ideal case, the reading light is supposed to be a conjugate wave of the reference light in which case the diffracted light becomes a convergent spherical wave in relation to the fiber. Using Eq. (2), each diffraction point on the plane of the fiber end can be simulated by calculating the interference between 30 rays moving toward the end of the fiber generated from the VHOE. Each ray comes from the interference of the diffracted lights. There are 50 diffraction centers located in the path of each ray that moves across the VHOE. Therefore, the diffraction intensity of each diffracted point on the fiber end is formed by the interference of light from 1500 diffraction centers. This sampling number is sufficient to obtain stable calculation results. When the sampling includes more diffraction centers in the simulation, there is no noticeable difference. In addition, the effect of the boundary refraction in the VHOE is also calculated.

Figs. 2 and 3 show the simulation of the lateral (x)/vertical (y) angular tolerance in the alignment, with respect to the distance *d* between the fiber end and the VHOE, for different reference angles (θ), during the writing process. The diffraction tolerance is defined by taking the half width of the first zero (called HWFZ) of the diffraction intensity. In Fig. 2, we find that the lateral angular tolerance becomes smaller when the distance between *d* and θ increases. The reason for the former case is that the recording area in the crystal becomes larger when *d* increases while the effective solid angle is limited by the single-mode fiber, whereas for the reason for the latter is that a larger θ causes a higher Bragg selectivity. In Fig. 3, we can see that the vertical angular tolerance decreases as *d* increases. However, from 0° to 60°, the vertical angular tolerance is independent of θ, owing to the Bragg degeneracy [2,21].

Figs. 2 and 3 indicate the characteristics of the simulated angular tolerance in the horizontal and vertical directions. However, if the reading light deviates slightly from the Bragg angle, we find that the diffracted spot moves. Figs. 4 and 5 show a simulation of the displacement as well as the diffraction efficiency of the diffracted spot when the angle of the reading beam deviates both horizontally and vertically, from the Bragg condition. The simulation also shows that the Bragg condition of the VHOE is more sensitive in the horizontal direction than that in the vertical direction. Additionally, the direction of the displacement of the diffracted spot is the same as that of the reading beam, both horizontally and vertically.

3. Experimental results and discussion

The experimental setup is shown in Fig. 6. A Verdi laser made by Coherent Inc. was used to produce the 532 nm laser light. The