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Image revivals in multi-mode optical fibers with periodic multiple sub-apertures

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ABSTRACT

We report experiments on a multi-mode fiber-based device that reimages the input pattern after specific propagation distances. The reimaging has two propagation length scales related to the Talbot self-imaging in a periodic grating and image revival effects. We use a beam propagation method to simulate diffraction and refraction of light in the optical fiber. The details of the fiber preparation and optical experiments are described. We study the optical imaging properties using a close-packed array of sub-apertures placed at regular positions on a triangular lattice. We numerically analyze the propagation, diffraction and coupling characteristics of the beam oscillating inside the fiber. Our simulations identify the optimal reimaging length of the multi-mode (MM) fiber to get high fidelity image revival. Experiments are performed to validate the simulation results.

1. Introduction

Since its first observation in the nineteenth century, the Talbot effect has drawn renewed attention from many researchers. It is one of several basic optical phenomena that is widely discussed in the literature. Recently the Talbot effect has become a useful tool for diverse applications including optical metrology [1], optical array illumination [2], matter wave self-imaging [3] and phase locking multiple amplifiers [4,5].

Among potential wide ranging applications, the design of phase-locked fiber lasers based on the Talbot effect and a revival of the image are of primary interest in this paper. Fiber lasers have been identified as promising candidates for developing high power lasers with a high degree of coherence [6,7]. One reason is the simple geometry of optical fibers, which make alignment relatively easy and the laser cavity compact. Also, optical fibers have inherently high surface area to active volume ratios which enable efficient cooling of the fiber system. Phase-locked fiber laser designs have been theoretically and experimentally demonstrated to be candidates for the future development of high power fiber lasers [8,9].

We propose the reimaging effect in multi-mode optical fibers as a method to reinforce phase locking between multiple fiber amplifiers. In a previous publication our calculations demonstrated how the use of reimaging could be useful for phasing the laser output and making the far-field laser spot coherent [4,5]. Here we report initial experiments to validate the reimaging concept using a tunable Ti:Sapphire laser whose wavelength spans the wavelength range from 740 nm to 840 nm. We find that the operation of a fiber-based device displays reimaging effects, which are related to the Talbot self-imaging and an image revival effect. The simulations are used to guide advanced experimental design of phase-lock laser sources.

2. Simulations for 37 phase-locked Gaussian beamlets

The multi-mode fiber (MMF) device for phase locking multiple, high power fiber amplifiers concept is introduced and discussed in Refs. [4,5]. In an all fiber laser application the field launched into the MMF is from a bundle of tapered and fused single mode (SM) fibers. On one end of the MMF, these input SM fibers are arranged in hexagonal rings with the same nearest-neighbor separation. The beams, or beamlets, from the input SM fibers are launched into the MM fiber, diffract and interfere with one another during propagation. Here the beams from the SM fibers are assumed to be Gaussian distributed. The propagating field diffracts out of the area where the SM fibers are centered and propagates to the core/clad boundary where it is reflected back toward the center of MMF. The image revival occurs when the reflected energy reforms the image of the input beams at the center of the core; this is the image revival distance.

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If the length of the MMF is controlled to be half of the revival distance, and a partial reflector is placed on the other end of the MM fiber, then the array of beamlets will be self-imaged into the input SM fibers, provided that all the input beamlets have the same phase. A partial reflector serves as an output coupler, and the far field of the output will be a small central spot. Since the waves do not interact with one another, this process can be viewed as a one-way propagation and the reflection is simply stretched out in the same direction.

In this section we model the all-fiber device with 37 input Gaussian beams with flat phase profile across each SM fiber input; the mode field diameter is assumed to be 10.4 μm. To compare our simulations to experiments we tune the input light wavelength between 740 nm and 840 nm. Also, we assume no phase and power variations between each hole in our simulations; the midpoint separation between two adjacent holes is 22 μm. The MM fiber (Thorlab's BFL37-400 fiber) used in our experiments has 400 μm core diameter, the core and cladding indices are reported to be 1.506 and 1.460, respectively and the numerical aperture is NA = 0.37. As mentioned earlier, the wave propagation is treated as a one-way propagation. Applying the beam propagation method (BPM) the dynamic field distribution can be easily and accurately determined as the beam propagates through the MM fiber.

In designing the experiment we use simulations to determine the position where the image repeats itself or at what distance the coupling efficiency is locally the highest. The normalized mode for the initial field, E_{x0}, is

$$f_{x0}=\frac{E_{x0}}{\sqrt{\int\int|E_{x0}|^2dx\,dy}}. \tag{1}$$

The field propagating at a distance z in the fiber is denoted as E_x; the total coupling efficiency at distance z is how well it overlaps with the initial field

$$\eta_1=\frac{\left|\iint f_{x0}E_x^*dx\,dy\right|}{\iint|E_x|^2dx\,dy}. \tag{2}$$

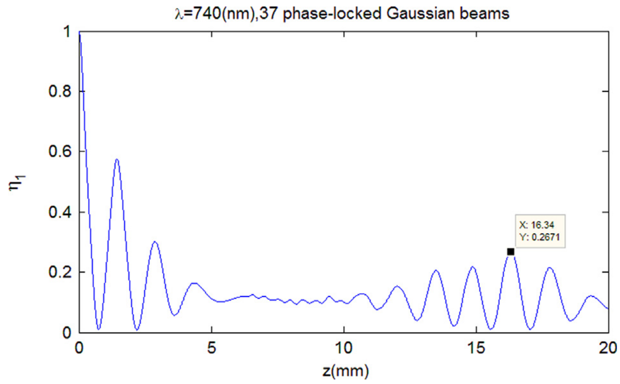

Fig. 1. Coupling efficiency for 37 Gaussian beams input at 740 nm.

The field $E_{x0}(x,y)$ is the initial input and the $E_x(x,y)$ is the field at distance z. The notation, E_x, indicates that the field is linearly polarized in the x-direction.

The coupling efficiency for 37 Gaussian beamlets input at 740 nm from our BPM simulations is shown in Fig. 1. The wave propagation is treated as one way propagation. In Fig. 1 the local oscillations leading to a maximum coupling efficiency occur at a distance 16.348 mm. We identify this as the revival distance for the maximum overlap of the input image with the revival image. We also observe a set of partial image revivals, which locally culminates in the peak overlap with the input image. The separation between local oscillations is determined by the Talbot imaging distance, which is estimated as $L_T=\pi d^2 n/2\lambda=1.54$ mm, where $\lambda=740$ nm is the wavelength in vacuum, d is the nearest-neighbor hole separation distance (22 μm) and n is the refractive index in the core. Note, in the real all-fiber device with the partial reflector, when the length of the MM fiber matches half of 16.348 mm which is 8.174 mm, the power coupling efficiency returning to the input ports will be maximized.

To estimate the revival distance based on Talbot imaging one might erroneously apply a formula: $L_r=\pi D^2 n/2\lambda=509$ nm, where D (=400 μm) is the core diameter of the MM fiber, n is the core index and λ is the wavelength in air. However, this distance is about 32 × greater than we observed in simulations and experiments. This estimate makes the assumption that on propagation, the reflections from the boundary of the MM fiber lead to a structure equivalent to a lattice consisting of the MM structure repeated every D. Clearly another process is responsible for the imaging. We infer that there is an angular rotation of the pattern due to excitation of many fiber modes with higher angular momentum values. The skew rays rotate about the center in an angular pattern and periodically recombine creating a partially phased image [10] at the revival distance.

Fig. 2 shows a plot of the initial input beams from the tapered and fused SM fiber bundle. The intensity and phase distributions of the field after propagating at a revival distance are plotted in Fig. 3. For a length of the MM fiber taken as the revival distance, i.e. 16.34 mm, the propagated beam has maximum overlap with the input beamlets. Furthermore, a Gaussian beam-like spot is found in the far field which is in space frequency domain and the distribution along k_x and k_y is shown in Fig. 4.

The reimaging distance as a function of the input wavelength is shown below in Fig. 5, where we determine that the revival distance decreases nearly linearly as the input wavelength increases.

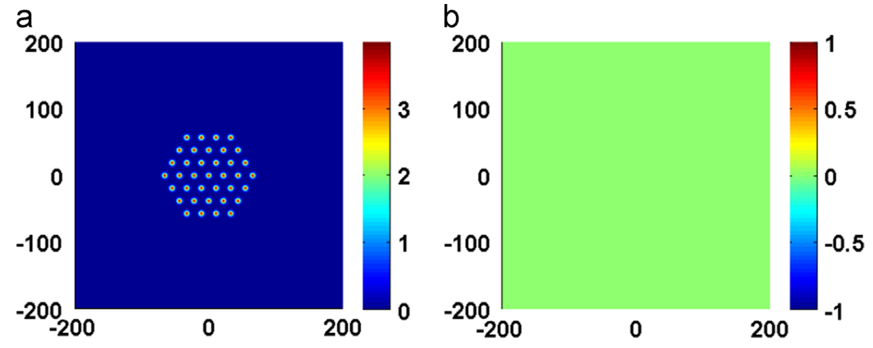

Fig. 2. Isometrically distributed inputs in MMF core: (a) intensity distribution of E_{x0} and (b) phase profile of E_{x0}.