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Polymer waveguides self-organized by two-photon photochemistry for self-aligned optical couplings with wide misalignment tolerances

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ABSTRACT

Self-organized optical waveguides formed in a photopolymer using two-photon photochemistry is proposed for self-aligned optical couplings involving nano-scale optical devices with wide tolerances in lateral misalignments. Simulations based on the finite-difference time-domain method revealed that on introducing a 400-nm write beam and a 780-nm write beam into the two-photon photopolymer respectively from two 600-nm-wide waveguides facing each other with 32 µm gap a self-aligned coupling waveguide called a two-photon self-organized lightwave network (SOLNET) is formed between the two waveguides. The lateral misalignment tolerance was found to be 3000 nm, which is five times larger than the misalignment limit of ~600 nm in waveguides formed by conventional one-photon photochemistry. Preliminary experiments demonstrated that the two-photon SOLNETs are formed between multimode optical fibers by introducing a 448-nm write beam and a 780-nm (or 856-nm) write beam from the fibers into a photosensitive organic/inorganic hybrid material, SUNCONNECT®, with doped camphorquinone (or biacetyl).

1. Introduction

Comprehensive work has been performed on optical interconnects [1–4] due to their high data rate and low power consumption characteristics [5]. In recent years, integrated optical interconnects with embedded thin-film optical devices [6–12] have been received much attention as the next-generation systems, including three-dimensional (3D) [11–18] and nano-scale-waveguide-based optical interconnects [14,19–21].

One of the technical issues in the optical interconnects is the coupling between optical devices because there are many optical coupling points in the systems. To date, edge couplings with mode converters [21] and grating couplings with tapered waveguides [14,22–24] have been developed. The former enables low-loss in-plane couplings with a loss smaller than 1 dB, and the latter enables low-loss vertical couplings. Despite these advantages, in the edge couplings, the cost for the optical coupling tends to be high because of process complexities and the requirements for accurate chip-dicing and alignment. In the grating couplings, the coarse wavelength division multiplexing is hard to be implemented because of their wavelength-sensitive characteristics.

To solve these problems, we previously proposed a coupling method based on a self-organized lightwave network (SOLNET) formed in photo-induced refractive-index increase (PRI) materials such as photopolymers by self-focusing [25,26]. Waveguide formation in photopolymers was first reported by Frisken [27]. An up-tapered waveguide was written by the emission of a write beam from a single-mode optical fiber core. Such a waveguide is called as self-written waveguide [28–30]. It was also constructed in photosensitive glass [31] and photorefractive crystals [32] to generalize the concept and widen the application fields. Meanwhile, SOLNET uses an attractive force between light beams in PRI materials. This allows formation of a self-aligned coupling waveguides between misaligned optical devices, and operates as an optical solder.

Recently, simulations based on the finite-difference time-domain (FDTD) method revealed that SOLNET can be applied to the nano-scale optical couplings [33,34]. The simulations, however, also revealed that the lateral misalignment tolerance is about 600 nm [33,34], which is insufficient for current accuracies of ~1 µm in chip bonding equipment [35].

In the present work, in order to extend the lateral misalignment tolerance, we proposed two-photon SOLNET [12,26,36], which uses two-photon photochemistry. The two-photon

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photochemistry has been reported by Brauchle et al. for holography in 1982 [37]. We predicted the lateral misalignment tolerance achieved in the two-photon SOLNET by the FDTD method to compare it with the tolerance achieved in the conventional one-photon SOLNET. We also formed two-photon SOLNETs experimentally between two multimode optical fibers to demonstrate viability of the two-photon SOLNET.

2. Concept of a two-photon SOLNET

In SOLNET, as illustrated in Fig. 1, optical devices such as optical fibers, waveguides, light modulators, laser diodes are placed in a PRI material, in which the refractive index increases by write-beam exposure. A write beam of wavelength λ_1 is introduced into the PRI material from one of the optical devices, while another write beam of wavelength λ_2 is introduced from the other optical device. The refractive index in the region, where the two write beams overlap, increases rapidly compared with that in the surrounding region. Thus, the two overlapping write beams merge into one through self-focusing to form a self-aligned coupling waveguide of the SOLNET between the optical devices, even if misalignments and core size mismatching exist.

In one-photon photochemistry, as shown in Fig. 2(a), chemical reactions are induced by a λ_1-write beam and a λ_2-write beam in parallel. Therefore, in a conventional one-photon SOLNET, the rate of the chemical reactions, specifically, the rate of the refractive index increase of the PRI material is proportional to I_1+I_2, where I_1 and I_2 are the intensities of the λ_1- and λ_2-write beams, respectively.

In two-photon photochemistry, as shown in Fig. 2(b), electrons excited by a λ_1-write beam from S_0 state to S_n state transfer to T_1 state, and then, they are further excited by a λ_2-write beam to T_n state to induce chemical reactions. Therefore, in the two-photon SOLNET, because a two-step electron excitation occurs in series, the rate of the refractive index increase is proportional to I_1I_2. Camphorquinone (CQ) and biacetyl (BA) are known as molecules that induce the two-photon photochemical reactions [37]. In the two-photon SOLNET the chemical reactions occur only if both λ_1- and λ_2-write beams coexist. This enhances the effect of the two-write-beam overlapping to extend tolerances in lateral misalignments.

3. Model and simulation procedure

Fig. 3 shows the model of simulations by the FDTD method. The core width of the input and output waveguides is 600 nm, and the core refractive index is 2.0. The refractive index of the PRI material increases from 1.5 to 1.7 upon write beam exposure, assuming the use of the PRI Sol–Gel material (Nissan Chemical Industries, Ltd.). The parameter of d expresses the lateral misalignment between the input and output waveguides.

λ_1 and λ_2 are assumed to be 400 nm and 780 nm, respectively, based on the absorption spectra of CQ and BA reported by Brauchle et al. [37]. The λ_1-write beam is emitted from the input waveguide and the λ_2-write beam from the output waveguide. A wavelength of 650 nm was used as probe beam, which propagates from the input waveguide to the output waveguide.

In the FDTD calculations [33,34], because the refractive index of the PRI material changes with time, its distribution is updated at each time step Δt. For one-photon SOLNET, since the rate of the refractive index increase is proportional to I_1+I_2, the refractive index change Δn during Δt can be expressed as

$$\Delta n = C_{1Photon}\left(E_1{}^2 + E_2{}^2\right)\Delta t, \quad (1)$$

$$C_{1Photon} = \frac{1}{2}\gamma\varepsilon v\ .$$

Here, ε is the dielectric constant, and v is the light velocity. E_1 and E_2 denote the respective electric fields for the λ_1- and λ_2-write beams. For simplicity, PRI material sensitivities for the two beams are set to the same value, γ.

For two-photon SOLNET, since the rate of the refractive index increase is proportional to I_1I_2, Δn during Δt can be expressed as

$$\Delta n = C_{2Photon}\left(E_1{}^2E_2{}^2\right)\Delta t. \quad (2)$$

The value of $C_{2Photon}$ was adjusted so that duration of SOLNET formation for a two-photon SOLNET is comparable to that for a one-photon SOLNET. This means adjusting the PRI material sensitivity. In the present study, we performed the simulations with $C_{2Photon} = 10^4 C_{1Photon}$.

The mesh sizes are $\Delta x=\Delta y=20$ nm, and $\Delta t=0.0134$ ps, which were chosen to satisfy convergence conditions in the FDTD calculations. In real systems, the typical PRI material response time is a few seconds or more. In the FDTD method, however, it is difficult to perform calculations with such long time spans, because Δt should be on a sub-ps scale. We therefore rescaled the time parameter in the results of the simulations as follows: $\Delta t' = \Delta t \times 10^{12}$ and $\gamma' = \gamma \times 10^{-12}$. This assumes the simulation refers to a PRI material with very high sensitivity. The polarization direction is perpendicular to the calculated plane. Because PRI materials are usually isotropic, polarization effects are likely to be negligible.

4. Results and discussions

4.1. FDTD Simulation of a two-photon SOLNET

Fig. 4 summarizes the simulation results. Here, the left- and right-hand columns represent the dielectric constant ε, i.e., the square of the refractive index n, and the intensity of the probe beams E^2, respectively.

In one-photon SOLNET, as shown in Fig. 4(a), for a lateral misalignment of 600 nm, a self-aligned coupling waveguide forms between the waveguides. The probe beam, which initially diffuses, becomes concentrated in the output waveguide with coupling efficiency of 85%. When the lateral misalignment is increased to 1800 nm or more, the self-aligned coupling waveguide is unable to form, and two waveguides extending from the input and output

Fig. 1. Concept of SOLNET.

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