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Self-aligned coupling waveguides experimentally formed by two-photon photochemistry for 3-D integrated optical interconnects

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ABSTRACT

We propose self-organized three-dimensional (3-D) integrated optical interconnects within computers, in which two-photon self-organized lightwave networks (two-photon SOLNETs) formed by two-photon photochemistry are implemented Previously reported simulation studies and initial fabrication demonstrations of two-photon TB-SOLNETs showed the possibility of enhanced self-aligned optical coupling as well as mode-size-converting functions, eliminating the connecting problems between misaligned optical devices. Nevertheless, in the TB-SOLNET, which requires two write beams to form, inserting the write beams and guiding them through the different devices to be interconnected is not a simple task. To remove the concern about insertion of write beams for SOLNET formation, other types of SOLNETs using either only one write beam and a luminescent target illuminated with the write beam (namely two-photon R-SOLNET), or simply two luminescent regions/targets illuminated with external excitation lights (two-photon P-SOLNET and LA-SOLNET) have been explored by means of simulations. In the present paper, preliminary experimental results for two-photon TB-SOLNETs and R-SOLNETs, including the coupling efficiency at a wavelength of 448 nm to couple two multimode optical fibers placed with a gap distance of 500 μm and different lateral misalignments, are shown for the first time. Experimental measurements reveal that two-photon TB-SOLNETs can overcome lateral misalignments of 40 μm with ~2.3 dB penalty, and two-photon R-SOLNETs with luminescent targets can be formed by one write beam to overcome misalignments of 25 μm with ~1.4 dB penalty. The experimental demonstration of TB-SOLNET hints to the potential feasibility of P-SOLNET since the formation dynamics for P-SOLNET are the same as for TB-SOLNET, and the experimental demonstration of R-SOLNET using placed luminescent targets hints to the feasibility of LA-SOLNET. These results indicate that the two-photon R-, P-, and LA-SOLNETs are expected as a novel low-cost method to fabricate 3-D integrated optical interconnects involving complex optoelectronic components in a self-organized manner. To prove further the validity of the proposed fabrication method for the optical interconnects, coupling efficiency measurements at telecom relevant wavelengths need to be performed in a next stage. Experiments for two-photon P- and LA-SOLNETs, and optimization of SOLNET formation conditions also remain as future work.

1. Introduction

Integrated optical interconnects, in which small/thin optoelectronic dies are embedded, have attracted much attention [1–15]. Three-dimensional (3-D) integrated optical interconnects within computers [1–9] are expected to realize energy-efficient, small-size, and low-cost systems. In the 3-D structures, the optical coupling between optical devices, especially those involving nanoscale waveguides [3,16–18], is a technical issue.

To date, edge couplings using mode size converters [18–20] and grating couplings combined with tapered waveguides [3,21–23] have been developed. The former provides low-loss in-plane couplings with a coupling loss smaller than 1 dB using tapered waveguide interfaces for the mode size conversion. However, the cost for the optical couplings becomes high due to the process complexity for the tapered waveguide fabrication and the requirements for accurate chip-dicing positions and alignments. The latter enables cost reductions for optical couplings and is useful for vertical couplings between stacked optical devices. However, it is hard to be applied to in-plane couplings, and, furthermore, not suitable for the coarse wavelength division multiplexing (CWDM) due to its wavelength-sensitive characteristics.

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To solve the coupling issue, we proposed an exotic optical coupling method based on the two-photon self-organized lightwave network (two-photon SOLNET) [24–27], which is formed in photosensitive materials utilizing two-photon photochemistry [28]. The two-photon SOLNETs are able to construct both in-plane and vertical self-aligned couplings with mode-size-converting functions, and are compatible with the 3-D wiring construction in the integrated optical interconnects. Since SOLNETs are wavelength-insensitive to exhibit wide spectral bandwidths, they are applicable to CWDM optical interconnects. The cost for the optical couplings is expected to be low due to the simple fabrication processes of SOLNETs as described in Section 2. Therefore, although they are a technology still in progress [24], the two-photon SOLNETs are regarded as a candidate for a simplified low-cost optical coupling method for the 3-D integrated optical interconnects.

We previously performed simulation studies based on the finite-difference time-domain (FDTD) method and initial fabrication demonstrations for two-beam-writing SOLNETs (TB-SOLNETs), which is the fundamental type of SOLNET, and revealed that the two-photon TB-SOLNETs exhibit optical solder capabilities with enhanced misalignment tolerances comparing to one-photon SOLNETs, which are formed utilizing conventional one-photon photochemistry [24,25,27]. These results confirmed the possibility that the two-photon TB-SOLNETs realize enhanced self-aligned optical couplings with mode-size-converting functions, eliminating the connecting problems between misaligned optical devices.

Nevertheless, in the TB-SOLNET, which requires two write beams to form, inserting the write beams and guiding them through the different devices to be interconnected is not a simple task. Namely, it is very hard to insert the write beams into optical coupling points in the 3-D structures, particularly, points in the inner parts because the write beams should pass through a large number of optical coupling points before they reach the destinations.

To remove the concern about the insertion of write beams for SOLNET formation, following three types of SOLNETs have been explored by means of the FDTD simulations.

- The reflective SOLNET (R-SOLNET) using only one write beam and a luminescent target illuminated with the write beam [6,7,24–26,29]
- The phosphor SOLNET (P-SOLNET) using simply two luminescent regions illuminated with external excitation lights [24,25]
- The luminescence-assisted SOLNET (LA-SOLNET) using two luminescent targets illuminated with external excitation lights [24,25]

In couplings between 600-nm-wide waveguides opposed with a 32-μm distance, the lateral misalignment tolerance to maintain <1 dB loss at 650 nm in wavelength was ∼2 μm, and the coupling loss at 1-μm lateral misalignment was ∼0.4 dB. In couplings between 3-μm-wide and 600-nm-wide waveguides, the coupling loss at 1-μm lateral misalignment was ∼0.9 dB. These simulation results suggested that the two-photon R-SOLNETs, P-SOLNETs, and LA-SOLNETs can be used as self-aligned optical couplings with mode-size-converting functions.

In the present work, we propose the concept of the self-organized 3-D integrated optical interconnects, in which two-photon R–SOLNETs, P-SOLNETs, and LA-SOLNETs are implemented, and describe the possible fabrication processes, namely, processes for the optoelectronic die embedding into films, the film stacking, and the two-photon SOLNET formation. Preliminary experimental results for two-photon TB-SOLNETs and R-SOLNETs, including the coupling efficiency of the two-photon SOLNETs formed between multimode optical fibers placed with a gap distance of 500 μm and different lateral misalignments, are presented for the first time. The possibility that the two-photon R-, P-, and LA-SOLNETs realize a novel low-cost method to fabricate the self-organized 3-D integrated optical interconnects is discussed.

2. Concepts for two-photon TB-SOLNET, P-SOLNET, R-SOLNET, and LA-SOLNET

Concepts for the TB-SOLNET, P-SOLNET, R-SOLNET, and LA-SOLNET are shown in Fig. 1. Optical devices such as optical waveguides, light modulators, optical switches, wavelength filters, laser diodes (LDs), and photodetectors (PDs) are placed in counter-direction arrangements with a photo-induced refractive-index increase (PRI) material filling in between. The PRI material, in which the refractive index increases by write beam exposure, can be photopolymers [30–35], photosensitive glass [36], photosensitive organic/inorganic hybrid materials [37,38], photorefractive materials [39,40], and third-order nonlinear optical materials.

In the TB-SOLNET, as Fig. 1(a) shows, a first write beam (write beam 1) of given wavelength λ_1 is introduced into a PRI material from an optical device while a second write beam (write beam 2) of given wavelength λ_2 is introduced from another optical device. The refractive index in the region, where the two write beams overlap, increases rapidly compared with that in the surrounding region. Then, because the two write beams tend to be confined in the higher-refractive-index region, they merge through self-focusing to form a self-aligned coupling waveguide of TB-SOLNET automatically between the optical devices, even if misalignments and core size mismatching exist between them.

In the P-SOLNET, as Fig. 1(b) shows, luminescent regions are formed in some parts of optical device cores to generate luminescence within the cores by external excitation lights from outside. Luminescence 1 of λ_1 and luminescence 2 of λ_2 respectively correspond to write beam 1 and write beam 2 in the TB-SOLNET. They form a self-aligned coupling waveguide of P-SOLNET. The same situation is available without the luminescent regions in the case that the waveguide cores are emissive intrinsically. For example, in silicon nitride (SiN) and silicon oxynitride (SiON) waveguides having emissive characteristics, luminescence for write beams can be generated within the cores just by exposing the cores to the external excitation lights. The P-SOLNET is effective when the write beams are difficult to be inserted into the cores.

As discussed previously [24,25], the formation dynamics model for the P-SOLNET is the same as that for the TB-SOLNET. This indicates that the results for the TB-SOLNET formation dynamics are regarded as those for the P-SOLNET formation dynamics at the same time.

In the R-SOLNET, as Fig. 1(c) shows, a luminescent target is placed on a front core edge of one of the optical devices. When a write beam of λ_1 is introduced from the other optical device into the PRI material, the target absorbs the write beam and emits luminescence of λ_2, which acts as the second write beam, to form a self-aligned coupling waveguide of R-SOLNET. The same situation is realized without the luminescent target in the case that the waveguide core has emissive characteristics intrinsically. The core edge plays the role of the luminescent target. The R-SOLNET is effective when the write beams cannot pass through one of the optical devices.

In the LA-SOLNET, as Fig. 1(d) shows, luminescent targets are placed on front core edges of both optical devices. By introducing external excitation lights from outside, the targets respectively emit luminescence 1 of λ_1 and luminescence 2 of λ_2 to form a self-aligned coupling waveguide of LA-SOLNET. The LA-SOLNET is effective when the write beams cannot pass through the optical devices.

In the one-photon SOLNETs, the λ_1-write beam excites electrons from S_0 to S_n state in sensitizing molecules to induce chemical reactions, specifically, an increase in the refractive index of the PRI material. In parallel, the λ_2-write beam excites electrons from S_0 to $S_{n'}$ state to induce an increase in the refractive index. In the two-photon SOLNETs, on the other hand, in two-photon absorption molecules, electrons excited from S_0 to S_n state by the λ_1-write beam transfer to T_1 state, and are further excited to T_n state by the λ_2-write beam, resulting in a refractive index increase. The two-step electron-excitation process in the two-photon SOLNET formation enhances the beam-overlapping effect to extend tolerances to misalignments and results in high-contrasting refractive-index images [24,25,27].