Vertical Optical Waveguide Comprising Square Base Cuboid Cores with Size Modulation for Multilayer Chip-to-Chip Interconnection

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Abstract: For chip-to-chip interconnection, a Pbit/s-class transmission capacity is expected to be developed in near future. To achieve such a huge capacity, a multilayer optical waveguide structure for connection between chips is indispensable. In this paper, a square base cuboid-core structure with size modulation for vertical light beam propagation in a polymer multilayer waveguide is proposed for improving optical coupling between the optical devices and waveguide. A 10-layer polymer waveguide with nonuniform cuboid cores are designed for single-mode transmission at 1.31 μm. Using a simulation based on the beam propagation method, it is confirmed that the proposed design can provide a coupling efficiency of −4.4 dB, which is 3.8 dB higher than that of a previously reported uniform cube-core design, for the 10-layer structure and a crosstalk of −20.6 dB. The simulated results show that the proposed nonuniform cuboid-core structure has the potential to realize a 10-layer optical waveguide structure for future chip-to-chip optical interconnection with a huge transmission capacity.

1 INTRODUCTION

With rapid progress in artificial intelligence, Internet of things, and other emerging IT technologies (Calo et al., 2017, Atlam et al, 2018), a strong demand for an increase in the transmission capacity of rack-to-rack, board-to-board, and chip-to-chip inter-connections has arisen. For chip-to-chip inter-connection, a Pbit/s-class capacity is expected in the near future. However, it is difficult for an electrical interconnection to achieve such a huge transmission capacity because of the problems of large transmission loss in the high-frequency region and significant heat generation. Therefore, optical chip-to-chip interconnection has attracted considerable attention owing to its high-speed and power-saving operation.

A typical optical chip-to-chip interconnection configuration is shown in Fig. 1 (Matsuoka et al., 2012). Two large-scale integration (LSI) chips adapted with optical interface devices are connected using an optical waveguide formed in the board. The optical signal from a vertical cavity surface-emitting laser (VCSEL) travels downward and is reflected by a 45° mirror for coupling to a horizontal waveguide. After being transmitted through the waveguide, the optical signal is reflected by another 45° mirror and detected by a photodiode (PD).

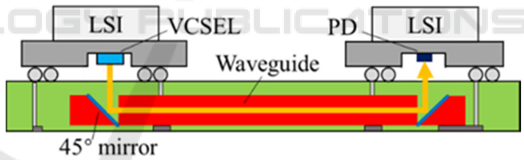

Figure 1: Schematic of an optical chip-to-chip interconnection.

Figure 1 shows an optical interconnection with a single layer waveguide. However, it is impossible to achieve Pbit/s-class capacity because of the limitation of the number of waveguides associated with the single layer. This means that a multilayer waveguide structure is indispensable for achieving a huge interconnection capacity.

There have been several studies on multilayer chip-to-chip interconnection (Shishikura et al., 2007, Suzuki et al., 2015). Figure 2 shows a cross-sectional schematic of a connection between the VCSELs and a multilayer optical waveguide. As shown, the optical signal travels a longer distance from the VCSEL to a waveguide in a deep position, and the light beam broadens before arriving at the mirror. This causes optical power loss and degrades

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the overall coupling efficiency between the VCSEL and photodiode (PD).

To solve this problem and increase the coupling efficiency, a multilayer optical printed wiring board with a cube-core structure has been proposed and demonstrated (Shishikura et al., 2007). The board contains a two-layer multimode waveguide for a wavelength of 0.85 µm.

For a rack- or board-level optical interconnection, 0.85-µm multimode VCSELs and multimode fiber (MMF) have been widely used. For the demonstration of chip-to-chip optical interconnection, the same type of VCSELs and multimode polymer waveguide have been mainly used (Ishii et al., 2003, Doany et al., 2012). However, in recent years, introduction of single-mode transmission to such a short-distance application has been actively discussed (Vyrsokinos et al., 2016) for meeting the demand of high-speed signal transmission over 25 Gbit/s without heavy digital signal processing at the receiver. Moreover, long-wavelength (1.31 or 1.55 µm) single-mode VCSELs operating around 50 Gbit/s (Spiga et al., 2017, Breyne et al., 2019) and single-mode polymer waveguide have been reported (Xu et al., 2017, Zuo et al., 2019).

In this work, the cube-core structure is applied to a multilayer single-mode polymer waveguide for a wavelength of 1.31 µm, and a new nonuniform cuboid-core structure design is proposed to provide high coupling efficiency for an optical interconnection board comprising 10 waveguide layers.

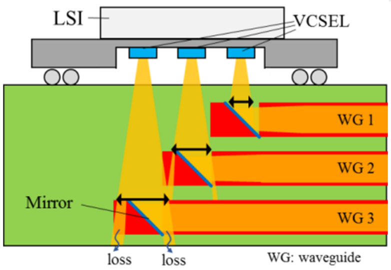

Figure 2: Cross-sectional schematic of a connection between VCSELs and a multilayer optical waveguide.

2 UNIFORM CUBE CORES

A cube-core structure was proposed and developed for a multilayer multimode optical waveguide (Shishikura et al., 2007). Figure 3(a) shows a cross-sectional schematic of the connection between the optical devices and the multilayer waveguide with cube cores. The cube-core structure acts like a lens or a waveguide core for vertical light beam propagation. The cube cores are composed of waveguide-core material and can be fabricated simultaneously in a waveguide-core fabrication process. They require no additional fabrication process as in conventional processes for fabrication of multilayer optical waveguides. As shown in Fig. 3 (b), this structure confines the light beam and suppresses the spread of the beam from the VCSEL. This leads to a high coupling efficiency between the optical devices and horizontal waveguides even in the lower layer.

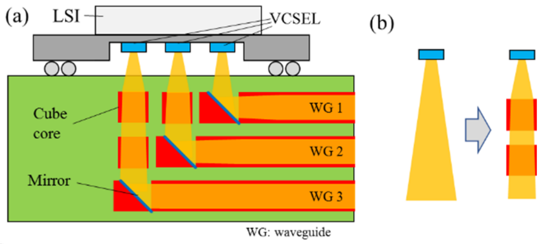

Figure 3: (a) Cross-sectional schematic of a connection between VCSELs and a multilayer optical waveguide with cube cores. (b) Optical confinement via cube cores.

By introducing the cube core, a vertical waveguide structure for a 10-layer single-mode waveguide was designed (Fig. 4). The design parameters are listed in Table 1. The operating wavelength was 1.31 µm. For a waveguide design in this study, ultraviolet (UV) curable acrylate polymers were set as the core and clad materials of the waveguide (ChemOptics Inc., 2019). The refractive indexes were set at 1.48 and 1.45 for the core and clad, respectively. A single-mode horizontal waveguide having a width of 3.0 µm and height of 3.0 µm was designed. In this work, the height of the cube core was fixed to 3.0 µm because the cube cores should be formed simultaneously with the waveguide core, as previously described. The size of the base area of all cube cores was set at 3.0 × 3.0 µm^2. The pitch between the cube cores, which is equal to the pitch of the layers, was fixed at 18 µm with consideration of a balance between the waveguide density and crosstalk.

The designed model was analyzed using the beam propagation method (BPM). Figures. 5(a) and (b) show simulated beam propagation diagrams for the 10-layer models without and with cube cores, respectively. It is obvious that the cube cores confine the light beam and guide it up to the 10th layer.

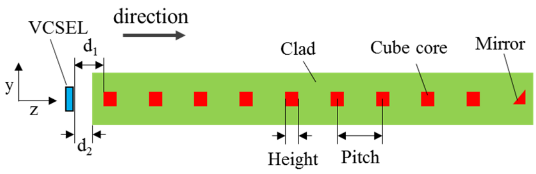

Figure 4: Model of the vertical waveguide comprising cube cores and a mirror.

Table 1: Design parameters.

Item	Value	
Wavelength	1.31 µm	
Waveguide mode	Single-mode	
Core height	3.0 µm	
Pitch	18 µm	
d_1 *1	10 µm	
d_2 *2	7 µm	
Refractive index	Clad	1.45
	Core	1.48

*1 d_1: Distance between VCSEL and the 1st core
*2 d_2: Distance between VCSEL and the layer surface

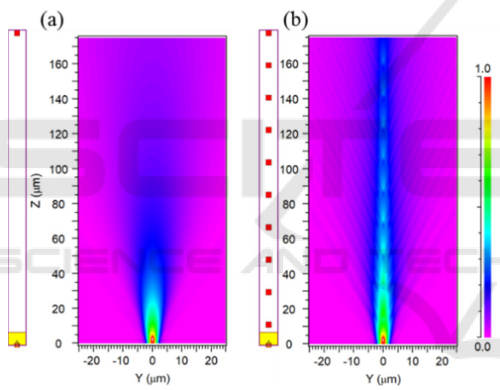

Figure 5: Simulated light beam propagation: (a) Without a cube core and (b) With a cube core.

To evaluate the effect of the cube-core structure, the coupling efficiency was calculated using models without and with cube cores. The coupling efficiency is the ratio of the monitored light power to the output light power of the VCSEL. At a propagation distance z, the light power in a monitor area was calculated and the coupling efficiency was obtained. In this work, the size of the monitor area was set at 5.2 × 5.2 µm^2, which is almost equal to the mode field size of the single-mode waveguide with a 3.0 × 3.0 µm^2 cross section. The z dependence of the coupling efficiency is shown in Fig. 6; the position of the input face of each cube core is shown with a marker on the curve. The cube-core structure effectively increases the coupling efficiency. In the 10th layer, the improvement is 7.6 dB; however, the coupling efficiency remains only −8.2 dB, which corresponds to a power loss of 85%. Even in the 5th layer, the coupling efficiency is less than −5 dB.

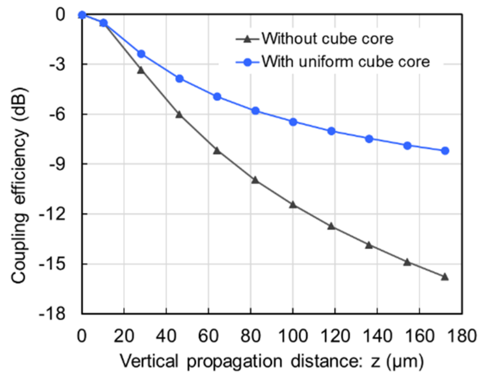

Figure 6: Coupling efficiency for the vertical waveguide with and without cube cores.

3 NONUNIFORM CUBOID CORES

To improve the coupling efficiency of the uniform cube-core structure, we propose square base cuboid cores with base-size modulation, as shown in Fig. 7(a). The cross-sectional size of the cuboid core gradually changes from the 1st to the 10th layer while its height is fixed to 3 µm. It is called a nonuniform cuboid-core structure in this paper. The simulated light beam propagation through the vertical waveguide consisting of 10 size-modulated cuboids is shown in Fig. 7 (b). Compared with the beam propagation of the uniform cube (Fig. 5(b)), the confinement of the light power is strengthened. The improvement is particularly obvious in the 8th. 9th and 10th layers.

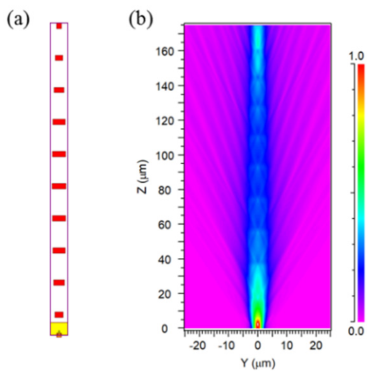

Figure 7: Nonuniform cuboid-core structure: (a) Schematic and (b) Simulated light beam propagation.

For the design of the 10-layer single-mode waveguide with a nonuniform cuboid-core structure (Fig. 8), the side lengths of the square base of the cuboid cores were optimized within a range of 3.0 – 8.0 µm with a 0.5-µm step for each layer. During the optimization process, the cuboid-core size in the lowest layer was fixed at 3.0 × 3.0 µm^2 because the 45° mirror was placed in this layer. Figure 9 shows the optimized square-base size of the cuboid cores for each vertical waveguide. As shown, the side length of the square base of the cuboid was gradually modulated.

For the optimized nonuniform cuboid-core design, the coupling efficiency was calculated (Fig. 10). The coupling efficiency of the uniform cube-core structure is also plotted for a comparison. The coupling efficiency of the nonuniform cuboid-core structure is significantly better than that of the uniform cube core for layer numbers greater than 4; it is greater than −5 dB for all layers. In the 10th layer, the coupling efficiency reaches −4.4 dB, which is 3.8 dB better than that of the uniform cube-core structure.

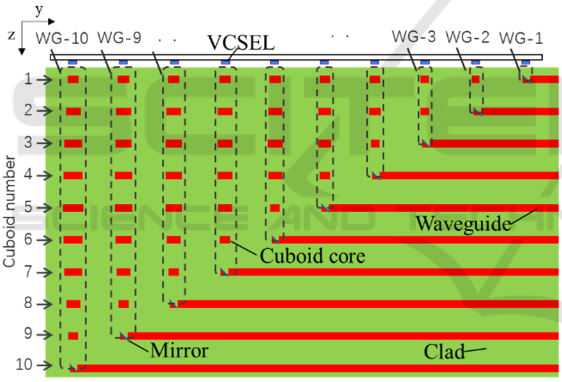

Figure 8: Schematic of the 10-layer single-mode waveguide with the nonuniform cuboid-core structure.

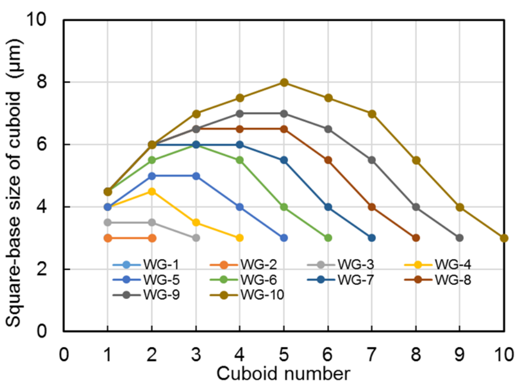

Figure 9: Optimized square-base size of cuboid core.

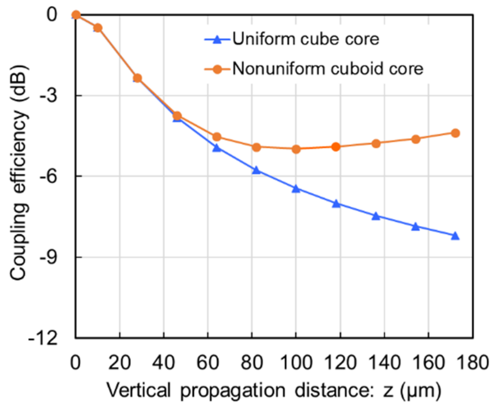

Figure 10: Coupling efficiency for the vertical waveguide with uniform cube cores and nonuniform cuboid cores.

For layer numbers greater than 6, the coupling efficiency of the nonuniform cuboid-core structure gently increases. It might be caused by a crude setting of the monitor area in the simulation.

In the multichannel interconnection, crosstalk between channels is an important issue. The crosstalk between adjacent channels was analyzed for both the uniform cube-core and nonuniform cuboid-core structures using the models shown in Fig. 11. In each model, two adjacent vertical waveguides with cuboid cores were designed with the channel pitch of 18 µm for the 10-layer waveguide.

The calculated crosstalk is shown in Fig. 12. With beam propagation in the vertical direction, the crosstalk increases. For both the uniform cube-core and nonuniform cuboid-core structures, the crosstalk is less than −30 dB up to the 3rd layer. It reaches approximately −20 dB in the 5th layer and remains at approximately −20 dB up to the 10th layer. Though the nonuniform cuboid-core structure can provide stronger optical confinement, it does not provide a significant improvement in the crosstalk; it has a crosstalk similar to that of the uniform cube-core structure. This result is probably because the crosstalk light from the adjacent channel can more readily couple with the larger cuboid cores. In the 10th layer, the crosstalks of the uniform cube-core and nonuniform cuboid-core structures are −18.1 dB and −20.6 dB, respectively; thus, an improvement of 2.5 dB was obtained.

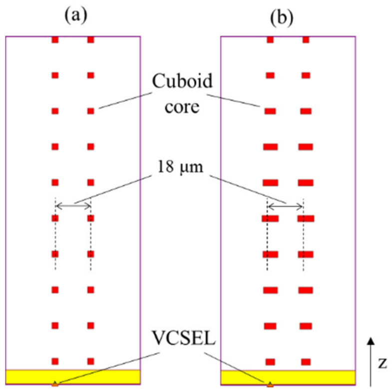

Figure 11: Crosstalk analysis models for the (a) uniform cube-core and (b) nonuniform cuboid-core structures.

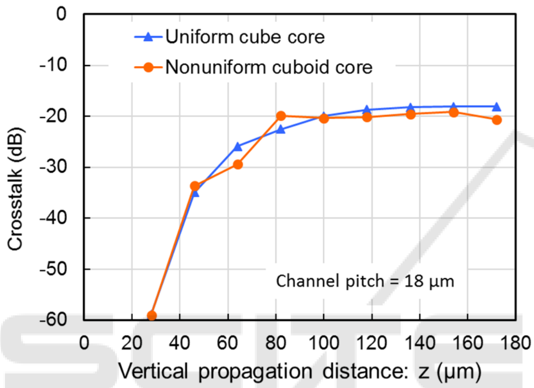

Figure 12: Crosstalk dependence on propagation distance.

4 CONCLUSIONS

For a Pbit/s-class chip-to-chip interconnection with a multilayer optical waveguide, cuboid-core structures for vertical light beam propagation were studied.

To solve the problem of poor optical coupling between the optical devices and waveguide in the lower layer, a cube-core structure was previously reported for improving the optical confinement of the vertical light beam propagation in a multilayer multimode waveguide. In this study, it was applied to the design of a multilayer single-mode waveguide for 1.31-μm light. In the simulation, the structure drastically improved the coupling efficiency; however, it could only provide a coupling efficiency of −8.2 dB for a 10-layer structure.

To further improve the coupling efficiency, a nonuniform square-base cuboid-core structure was proposed. The base size of the cuboid gradually changed along with the light beam propagation. The new design showed a coupling efficiency of −4.4 dB for a 10-layer structure and provided a crosstalk of −20.6 dB, which is 2.5 dB less than that of the uniform structure.

These simulated results show that using the proposed nonuniform cuboid-core structure, a 10-layer single-mode polymer waveguide structure for chip-to-chip optical interconnection with a huge transmission capacity can be realized.

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