論文 / 著書情報
Article / Book Information

題目(和文)	
Title(English)	Study on 1060nm VCSEL arrays for co-packaged optics
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出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第12694号, 授与年月日:2024年3月26日, 学位の種別:課程博士, 審査員:植之原 裕行,小山 二三夫,中村 健太郎,西山 伸彦,宮本 智之,渡辺 正裕,粕川 秋彦
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第12694号, Conferred date:2024/3/26, Degree Type:Course doctor, Examiner:,,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	論文要旨
Type(English)	Summary

（博士課程）
Doctoral Program

論 文 要 旨

THESIS SUMMARY

系・コース： Department of, Graduate major in	電気電子 電気電子	系 コース	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of	（ 工学 ）
学生氏名： Student's Name	DONG LIANG		審査員主査： Chief Examiner	植之原裕行	

要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Summary

In the realm of next-generation communication systems, the integration of Co-Packaged Optics (CPO) emerges as a pivotal innovation, primarily due to its high-density and low power consumption attributes. This doctoral thesis presents a comprehensive study and development of Vertical-Cavity Surface-Emitting Laser (VCSEL) Array tailored for CPO applications. The research delineates the design, structure, fabrication process, characterization, and high-speed modulation characteristics of VCSEL arrays and their optical coupling with multi-core fibers (MCF).

VCSELs: An Optimal Choice for CPO:

VCSEL stands out as a superior optical resource for CPO, owing to the advantages such as high-speed data transmission capabilities, low power consumption, small footprint, cost-effectiveness, ease of testing on a wafer-scale, simplicity of fabricating into array and its circle beam for fiber coupling. Such attributes render VCSELs not only practical but also highly efficient for the demands of advanced optical communication systems.

Designing VCSEL Arrays for CPO:

The thesis details the design of a 16-channel bottom-emitting VCSEL array, specifically engineered for the 1060 nm-band, targeting single-mode multi-core fiber transmission. This VCSEL array showcases a compact layout where each channel is meticulously spaced at 40 μm. The array's cores and electrode pads are totally sized at 400 μm, and the total pitch size of the array chip is 900 μm. This design reflects a meticulous balance between compactness and performance, catering to the high-density requirements of CPO optical transceivers.

Structural Insights and Characterization of 1060nm VCSEL Arrays:

A critical aspect of the research involves the structural formation and characterization of the VCSEL arrays. A key feature is the transverse coupled cavity, achievable with a boundary gap ranging from 0.5 to 1.5 μm between the oxidation aperture and contact metal. This structure facilitates single-mode operation in larger oxidation aperture devices through the Vernier effect. Additionally, the manipulation of the resonant wavelength between regions with and without surface relief contributes to enhanced side-mode suppression ratios (SMSR).

In this thesis, the internal fabrication process and fabrication process based on 3-inch wafers are detailly introduced.

In the realm of performance, bottom-emitting VCSEL arrays with a 5 μm oxidation aperture demonstrate a typical output power of 2.5-3.5 mW and a threshold current between 0.6 to 0.8 mA. These arrays maintain single-mode operation across the entire current range, exhibiting exceptional uniformity. Thermal crosstalk is another critical factor, with bottom-emitting VCSELs showing a total thermal crosstalk of 18K at 6mA. It can be reduced after flip-chip bonding process.

High-Speed Modulation Characteristics:

The high-speed modulation capabilities of these VCSEL arrays represent a significant leap compared with conventional VCSELs. With the incorporation of a transverse coupled cavity and surface-relief structures, along with the reduction of parasitic elements, the arrays achieve a small signal response of 23 GHz at 6mA. A groundbreaking accomplishment is the demonstration of noiseless 25Gbps eye patterns across 16 channels, achieving an unprecedented total transmission capacity of 400Gbps. This achievement is a first in the field, highlighting the potential of densely integrated VCSEL arrays in high-speed data transmission.

Further experiments reveal impressive signal-to-error ratios (SER) and Transmitter and Dispersion Eye Closure Quaternary (TDECQ) values for various NRZ and PAM4 signals, both with and without pre-equalization. The use of pulse compression techniques in tandem with negative fiber dispersion and frequency chirp leads to significant bandwidth enhancements. The arrays successfully transmit data

over distances up to 5km, maintaining open eye patterns for 60Gbps NRZ and 70Gbps PAM-4 signals after 5km, marking a significant milestone in VCSEL-SMF communication.

Optical Coupling with Multi-Core Fiber (MCF):

The integration of the VCSEL array with a fabricated 19-core single-mode MCF is a vital component of this research. The MCF features a 40 μm core spacing and a 220 μm diameter, with a mode field diameter (MFD) of 6.5 μm at 1060nm. The VCSEL array is meticulously packaged using flip-chip bonding, achieving a calculated coupling loss of 1dB with the MCF when the VCSEL MFD is 6 μm. Experimental findings highlight the challenges and successes of direct coupling. The research also assesses the alignment tolerances, further demonstrating the practicality of VCSEL and MCF integration in real-world applications.

Conclusion:

This doctoral thesis represents a significant advancement in the field of optical communications, particularly in the context of CPO using VCSEL arrays. The research not only demonstrates the feasibility of integrating densely packed, high-speed VCSEL arrays into modern communication systems but also paves the way for future innovations in this rapidly evolving field. The findings hold immense promise for further optimization of VCSEL arrays, potentially leading to even higher data transmission rates and broader applications in more complex optical systems.