論文 / 著書情報
Article / Book Information

題目(和文)	共振器内表面構造制御VCSELのモード制御と帯域幅向上に関する研究
Title(English)	Study on Mode Control and Bandwidth Enhancement of Intra-cavity Surface Engineered VCSELs
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Category(English)	Doctoral Thesis
種別(和文)	論文要旨
Type(English)	Summary

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

In this thesis, the principle of mode control and bandwidth enhancement was demonstrated. Specifically, the achievement of single-mode operation and enhanced bandwidth is demonstrated through the utilization of intra-cavity surface relief metal-aperture VCSELs and surface grating loaded VCSELs. The thesis encompasses the simulation, fabrication process, and measurements of these devices, providing a comprehensive overview of their performance.

Mode control and bandwidth enhancement method

The concept of mode control and bandwidth enhancement is successfully demonstrated in this study. Through simulation, it has been observed that the metal-aperture half-cavity VCSEL allows for further expansion of the small signal modulation bandwidth due to photon-photon resonance occurring within a short distance (<2μm) between the oxidation aperture and the p-contact metal boundary. The transverse coupling strength plays a crucial role in achieving bandwidth enhancement, as it provides mode selectivity and enables stable single-mode operation. For short cavity VCSELs, the incorporation of a metal aperture proves to be an effective method for mode control. For longer cavity lengths, a surface grating loaded coupled cavity VCSEL is introduced, wherein the surface grating controls the transverse modes, while the coupled cavity structure provides optical feedback, enabling the realization of the photon-photon resonance effect and thus enhancing the bandwidth.

Intra-cavity metal-aperture VCSEL

The fabrication process of intra-cavity surface relief metal-aperture VCSELs is successfully demonstrated. By implementing a surface relief technique with a depth of 30nm, stable single-mode operation is achieved across the entire current range, utilizing oxidation apertures of 5μm, 6μm, and even 7μm. The output power of the device with a 5μm oxidation aperture can reach 2.5mW, which can be further increased to over 3mW by reducing the reflectivity of the dielectric DBR. A record-breaking small signal bandwidth of 31GHz is achieved by parasitic optimization process. Moreover, the VCSELs exhibit excellent temperature robustness, enabling uncooled operation. Stable single-mode operation is maintained across the entire current range, even at elevated temperatures up to 85°C.

Single-mode fiber data transmission

Thanks to the pulse compression effect resulting from fiber negative dispersion and frequency chirp, the small signal modulation bandwidth extends to 35GHz, 32GHz, and 25GHz over transmission distances of 2km, 5km, and 10km, respectively, through SMF. Additionally, we have successfully demonstrated high-speed large signal modulations, achieving 70Gbps (NRZ) and 110Gbps (PAM4) transmissions over a 2km distance using 1300nm-SMF. Notably, we extended the link length to 10km at a 45Gbps (NRZ) rate, which is a hundredfold improvement compared to 850nm MMF links. The achieved bandwidth-distance product amounts to 450Gbps•km. Furthermore, with the assistance of digital signal processing (DSP) in offline mode, a data rate of up to 128Gbaud has been accomplished. Thanks to its excellent temperature tolerance, the small signal modulation bandwidth reaches 27GHz, enabling 70Gbps (NRZ) and 100Gbps (PAM4) data transmissions over 2km of single-mode fiber.

Design of surface grating VCSEL

We conducted modeling of surface grating-loaded VCSELs based on the coupled-mode theory, incorporating the slow-wave effect. This approach predicts a narrower stopband in surface grating-loaded VCSELs, facilitated by the slow-wave propagation resulting from significant waveguide dispersion. Our simulations indicate that a wide range of control over coupling coefficients allows for long-cavity VCSELs up to 10mm in length, as well as short-cavity devices as small as 10μm, in surface grating-loaded VCSELs. For a 10mm-long device, employing a structure with a 10nm grating depth, 19 pairs of top-DBR, and an 8th order grating enables single-mode operation with a low threshold. In the case of short-cavity devices spanning around a hundred micrometers, reducing the top-DBR to 5 pairs allows for the formation of a 10μm-long grating-loaded VCSEL with a 30nm grating depth. Consequently, our proposed VCSEL platform, employing surface grating structures, offers a wide range of device lengths, from 10μm to 10mm, catering to diverse applications in VCSEL photonics.

Fabrication and characterization of surface grating VCSEL

The fabrication process of grating loaded VCSELs with coupled cavities is conducted. The difference is the first order surface grating formed on the wafer at the first step. Additionally, taper sides are incorporated to reduce one-sided reflectivity. With a device length of 200μm, slow light lasing is achieved at 1045nm, exhibiting an emission angle of 60 degrees. However, the high reflectivity of the dielectric DBR in the 1060nm band results in vertical emission. Furthermore,

a coupled cavity VCSEL with a 600μm-long cavity demonstrates stable quasi-single mode operation. Vertical emission is achieved through the utilization of a second-order grating; however, two additional modes also emerge with approximately two-thirds of the total intensity. The simulation of a second order grating half-cavity VCSEL is illustrated, showcasing the potential of vertical emission surface grating VCSEL arrays for achieving data transmission rates of 1.6Tbps, 3.2Tbps, 6.4Tbps, and beyond.