Hybrid Si-on-chip Lasers with Nano Structures

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Hybrid grating reflectors: Origin of ultrabroad stopband
Hybrid grating (HG) reflectors with a high-refractive-index cap layer added onto a high contrast grating (HCG) provide a high reflectance close to 100% over a broader wavelength range than HCGs. The combination of a cap layer and a grating layer brings a strong Fabry-Perot (FP) resonance as well as a weak guided mode (GM) resonance. Most of the reflected power results from the FP resonance, while the GM resonance plays a key role in achieving a reflectance close to 100% as well as broadening the stopband. An HG sample with 7 InGaAlAs quantum wells included in the cap layer has been fabricated by directly wafer-bonding a III-V cap layer onto a Si grating layer. Its reflection property has been characterized. This heterogeneously integrated HG reflector may allow for a hybrid III-V on Si laser to be thermally efficient, which has promising prospects for silicon photonics light sources and high-speed operation.

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Hybrid III-V on Si grating as a broadband reflector and a high-Q resonator

Hybrid grating (HG) with a high-refractive-index cap layer added onto a high contrast grating (HCG), can provide a high reflectance close 100% over a broader wavelength range than HCGs, or work as a ultrahigh quality (Q) factor resonator. The reflection and resonance properties of HGs have been investigated and the mechanisms leading to these properties are discussed. A HG reflector sample integrating a III-V cap layer with InGaAlAs quantum wells onto a Si grating has been fabricated and its reflection property has been characterized. The HG-based lasers have a promising prospect for silicon photonics light source or high-speed laser applications.

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Hybrid III-V/SOI resonant cavity enhanced photodetector

A hybrid III–V/SOI resonant-cavity-enhanced photodetector (RCE-PD) structure comprising a high-contrast grating (HCG) reflector, a hybrid grating (HG) reflector, and an air cavity between them, has been proposed and investigated. In the proposed structure, a light absorbing material is integrated as part of the HG reflector, enabling a very compact vertical cavity. Numerical investigations show that a quantum efficiency close to 100% and a detection linewidth of about 1 nm can be achieved, which are desirable for wavelength division multiplexing applications. Based on these results, a hybrid RCE-PD sample has been fabricated by heterogeneously integrating an InP-based material onto a silicon-on-insulator wafer and has been characterized, which shows a clear enhancement in photo-current at the designed wavelength. This indicates that the HG reflector provides a field enhancement sufficient for RCE-PD operation. In addition, a capability of feasibly selecting the detection wavelength during fabrication as well as a possibility of realizing silicon-integrated bidirectional transceivers are discussed.

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Hybrid III-V/SOI Resonant Cavity Photodetector

A hybrid III-V/SOI resonant cavity photo detector has been demonstrated, which comprises an InP grating reflector and a Si grating reflector. It can selectively detects an incident light with 1.54-µm wavelength and TM polarization.

Ultrabroadband Hybrid III-V/SOI Grating Reflector for On-chip Lasers

We report on a new type of III-V/SOI grating reflector with a broad stopband of 350 nm. This reflector has promising prospects for applications in high-speed III-V/SOI vertical cavity lasers with an improved heat dissipation capability.
Ultrahigh-speed Si-integrated on-chip laser with tailored dynamic characteristics

For on-chip interconnects, an ideal light source should have an ultralow energy consumption per bandwidth (operating energy) as well as sufficient output power for error-free detection. Nanocavity lasers have been considered the most ideal for smaller operating energy. However, they have a challenge in obtaining a sufficient output power. Here, as an alternative, we propose an ultrahigh-speed microcavity laser structure, based on a vertical cavity with a high-contrast grating (HCG) mirror for transverse magnetic (TM) polarisation. By using the TM HCG, a very small mode volume and an un-pumped compact optical feedback structure can be realised, which together tailor the frequency response function for achieving a very high speed at low injection currents. Furthermore, light can be emitted laterally into a Si waveguide. From an 1.54-μm optically-pumped laser, a 3-dB frequency of 27 GHz was obtained at a pumping level corresponding to sub-mA. Using measured 3-dB frequencies and calculated equivalent currents, the modulation current efficiency factor (MCEF) is estimated to be 42.1 GHz/mA(1/2), which is superior among microcavity lasers. This shows a high potential for a very high speed at low injection currents or a very small heat generation at high bitrates, which are highly desirable for both on-chip and off-chip applications.
Vertical-cavity laser with a novel grating mirror

Hybrid III-V on silicon (Si) ‘vertical cavity lasers’ (hybrid VCLs), which can emit light laterally into a Si waveguide, are fabricated and investigated. The Si-integrated hybrid VCL consists of a top dielectric Bragg reflector (DBR), a III-V active layer, and a bottom high contrast grating (HCG) mirror formed in the Si layer of a Si-on-insulator (SOI) wafer. The hybrid VCLs have a promising potential for very high-speed operation and low energy consumption, which is ideal for optical interconnects as well as large data center applications. For the experimental demonstration of hybrid VCLs, CMOS-compatible fabrication processes are designed and developed. These include a low-temperature direct wafer bonding process for integrating III-V layers onto a SOI wafer, as well as two types of DBR formation processes: a lift-off process and an etch-back process. Based on these, two versions of optically-pumped hybrid VCLs have been fabricated. The first version of hybrid VCL is designed for demonstrating in-plane emission into a Si waveguide. The in-plane emission is enabled by the bottom HCG abutting the Si waveguide, which not only functions as a highly reflective mirror but also routes the light from the vertical cavity laterally into the Si waveguide. The measured in-plane emission proves the lasing action with a side-mode suppression ratio (SMSR) of 27.5 dB at a peak wavelength of 1486 nm. The threshold pumping power corresponds to a current injection of 1.1 mA. A signature of highly anisotropic cavity dispersion has been observed and discussed, which is unique for HCG-based vertical cavities. The second version proves the potential for high-speed operation of hybrid VCL structure. In the hybrid VCL structure, the effective cavity length is substantially reduced by using a dielectric DBR and a TM-HCG with a very short evanescent tail. This reduces the photon lifetime of the laser cavity significantly without reducing the mirror reflectivity, leading to a very high intrinsic speed. A 3 dB frequency of 27.2 GHz was measured at a pumping power corresponding to a current injection of 0.7 mA. Since the pumping power was limited by the setup, the 3 dB frequency could be even higher. At this pumping level, the SMSR was about 49 dB and the lasing wavelength was 1541 nm. It was noteworthy that a modulation current efficiency factor (MCEF) of 42.1 GHz/mA1/2, which is 3 times greater than the cutting edge 850 nm VCSEL. Besides, this large MCEF is desirable for significantly lowering the injection current at a given target speed, which implies the amount of heat generation can potentially be reduced by 2 orders of magnitude than the 850 nm VCSELs.

Last, a new type of grating reflector, referred to as hybrid grating (HG) is analyzed and demonstrated, which may improve the heat dissipation efficiency of HCG-based hybrid VCL structures. The HG mirror consisting of a bottom grating and a high-refractive-index cap layer integrated on the grating can provide a stop band even broader than HCG. The interaction between the cap and the bottom grating results in strong Fabry-Perot (FP) resonance as well as weak guided mode (GM) resonance. Most of the reflected power come from the FP resonance while the GM resonance performs a crucial role in achieving a reflectance of almost 100% as well as broadening the stopband as wide as 300 nm.
Hybrid III-V/SOI single-mode vertical-cavity laser with in-plane emission into a silicon waveguide

We report a III-V-on-SOI vertical-cavity laser emitting into an in-plane Si waveguide fabricated by using CMOS-compatible processes. The fabricated laser operates at 1.54 µm with a SMSR of 33 dB and a low threshold.

Hybrid vertical-cavity laser with lateral emission into a silicon waveguide

We experimentally demonstrate an optically-pumped III-V/Si vertical-cavity laser with lateral emission into a silicon waveguide. This on-chip hybrid laser comprises a distributed Bragg reflector, a III-V active layer, and a high-contrast grating reflector, which simultaneously funnels light into the waveguide integrated with the laser. This laser has the advantages of long-wavelength vertical-cavity surface-emitting lasers, such as low threshold and high side-mode suppression ratio, while allowing integration with silicon photonic circuits, and is fabricated using CMOS compatible processes. It has the potential for ultrahigh-speed operation beyond 100 Gbit/s and features a novel mechanism for transverse mode control.
III-V/SOI vertical cavity laser structure for 120 Gbit/s speed

Ultrashort-cavity structure for III-V/SOI vertical cavity laser with light output into a Si waveguide is proposed, enabling 17 fJ/bit efficiency or 120 Gbit/s speed. Experimentally, 27-GHz bandwidth is demonstrated at 3.5 times of threshold. © 2015 OSA.

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III-V/SOI vertical cavity laser with in-plane output into a Si waveguide
We experimentally demonstrate an optically-pumped III-V-on-SOI hybrid vertical-cavity laser that outputs light into an in-plane Si waveguide, using CMOS-compatible processes. The laser operates at 1.49 $\mu$m with a side-mode suppression-ratio of 27 dB and has a similar threshold as long-wavelength VCSELs.

Polarization-Independent Wideband High-Index-Contrast Grating Mirror
Island-type two-dimensional high-index-contrast grating mirror based on a standard silicon-on-insulator wafer have been experimentally demonstrated. The measured spectra shows a bandwidth of ~192 nm with a reflectivity over 99% as well as polarization independence. Numerical simulations show that the designed mirror has large tolerance to fabrication errors.
Hybrid grating reflector with high reflectivity and broad bandwidth

We suggest a new type of grating reflector denoted hybrid grating (HG) which shows large reflectivity in a broad wavelength range and has a structure suitable for realizing a vertical cavity laser with ultra-small modal volume. The properties of the grating reflector are investigated numerically and explained. The HG consists of an un-patterned III-V layer and a Si grating. The III-V layer has a thickness comparable to the grating layer, introduces more guided mode resonances and significantly increases the bandwidth of the reflector compared to the well-known high-index-contrast grating (HCG). By using an active III-V layer, a laser can be realized where the gain region is integrated into the mirror itself.

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Hybrid III-V-on-Si Vertical Cavity Laser for Optical Interconnects

Combining a III-V active material onto the Si platform is an attractive approach for silicon photonics light source. We have developed fabrication methods for novel III-V on Si vertical cavity lasers.

Ultrahigh-speed hybrid laser for silicon photonic integrated chips

Increasing power consumption for electrical interconnects between and inside chips is posing a real challenge to continue the performance scaling of processors/computers as predicted by D. Moore. In recent processors, energy consumption for electrical interconnects is half of power supplied and will be 80% in near future. This challenge strongly has motivated replacing electrical interconnects with optical ones even in chip level communications [1]. This chip-level optical interconnects need quite different performance of optoelectronic devices than required for conventional optical communications. For a light source, the energy consumption per sending a bit is required to be <10 fJ/bit for on-chip interconnects and <100 fJ/bit for off-chip interconnects; this is two or three orders of magnitude smaller than the conventional devices. To meet the energy/bit requirement, many innovative laser diode and light-emitting diode (LED) structures have been proposed so far. Our hybrid laser is one of these efforts [2].

The hybrid laser consists of a dielectric reflector, a III-V semiconductor active material, and a high-index-contrast grating (HCG) reflector formed in the silicon layer of a silicon-on-insulator (SOI) wafer. ‘Hybrid’ indicates that a III-V active material is wafer-bonded to a silicon SOI wafer. In the hybrid laser, light is vertically amplified between the dielectric and the HCG reflectors, while the light output is laterally emitted to a normal Si ridge waveguide that is connected to the HCG reflector. The HCG works as a vertical mirror as well as a vertical-to-lateral coupler. Very small field penetration into the HCG allows for 3-4 times smaller modal volume than typical vertical-cavity surface-emitting lasers (VCSELs). This leads to high direct modulation speed. Details on device operating mechanism will be explained in the lecture.

Recently, a nano light-emitting diode (LED) with energy/bit < 1fJ/bit [3] and a nano laser diode with a buried heterostructure (BH) active material [4] have been recently reported in the literature. Additionally, device physics, engineering issue, and error-free light detection issue in quantum limit will be discussed in relation to these two structures.
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