Generating Short-Wavelength Light Using a Vertical-Cavity Laser Structure

Second-harmonic generation from a GaAs/AlAs vertical cavity fabricated on a (311)B GaAs substrate has been demonstrated. The experimental results and a theoretical analysis show that a GaAs/AlAs vertical cavity optimized both for efficient confinement of the fundamental power and for quasi-phase-matching can offer efficient second-harmonic generation.

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There has been great interest in compact short-wavelength light sources, especially blue light sources, for a number of applications such as full-color displays and high-density optical storage. Full-color displays require compact light sources of three colors: red, green, and blue. Red light sources have been developed and are commercially available in the form of AlGaAs laser diodes and light-emitting diodes (LEDs). Green LEDs have recently become commercially available as well. Compact devices emitting blue light have been demonstrated, but their reliability is not good enough for commercial products. Optical storage uses laser diodes to read and write data. Shorter-wavelength laser diodes can give higher storage density. Blue lasers can store data at about three times the density achievable with the infrared lasers currently used for optical storage.

A laser diode made of a wide-bandgap semiconductor such as zinc cadmium sulfur selenium (ZnCdSSe) is one of the approaches being taken to realize compact blue light sources.[1,2] The advantages of this device include compact size and direct modulation of blue light. The feasibility of such a device has been demonstrated, but its reliability is not yet good enough for commercial applications.

Another approach being taken to make compact short-wavelength light sources is second-harmonic generation. In nonlinear optical materials, a fraction of the propagating fundamental optical wave is converted to an optical wave of double the frequency or half the wavelength. Using this second-harmonic generation technique, blue light at a wavelength of 430 to 490 nm has been generated from an infrared light of wavelength 860 to 980 nm. Reliable and compact short-wavelength blue light sources have been prototyped employing nonlinear dielectric materials such as lithium tantalate ($LiTaO_3$) and lithium niobate ($LiNbO_3$).[3-5] However, these second-harmonic generation blue light sources are hybrid and much larger in size than laser diodes.

Second-harmonic generation to realize compact short-wavelength light sources has been demonstrated in semiconductors such as GaAs and AlGaAs.[6-12] Second-harmonic generation in semiconductors can bring about monolithic short-wavelength light sources, since semiconductors like GaAs or AlGaAs can work as both laser materials and second-harmonic generation materials simultaneously. In some devices, a stack of GaAs and AlGaAs with a period of half a wavelength of the second harmonic has been incorporated to give quasi-phase-matched second-harmonic generation.[10-12] In most optical materials, the refractive index changes depending on the wavelength, causing a phase difference between the propagating fundamental light and the propagating second-harmonic light. The phase of the generated second-harmonic light is exactly twice that of the propagating fundamental light, so it is different from the phase of the propagating second-harmonic light, resulting in negative interference between the generated second-harmonic light and the propagating second-harmonic light. For some crystals, it is possible to cancel this phase difference and negative interference by choosing a certain axis for the light propagation direction. This is called phase matching. Another way to reduce the negative interference is by alternating the magnitude or sign of the generated second-harmonic field in phase with the phase difference. This phase-matching scheme does not eliminate the negative interference completely and so it is called quasi-phase-matching.

The second-harmonic power coming out of a GaAs/AlGaAs second-harmonic generator gets saturated in a limited distance because of the large absorption of second-harmonic power by GaAs or AlGaAs. To extract the second-harmonic power efficiently, most of the GaAs second-harmonic generators reported so far are surface emitters. The second-harmonic wave comes out normal to the surface after propagating through only a small distance in the absorbing semiconductor.[7,8,9,11,12] One way to increase the conversion efficiency in the limited GaAs/AlGaAs distance is to resonate the fundamental field with a Fabry-Perot cavity and to increase the intensity of the fundamental field inside the region, since second-harmonic power has a second-order dependence on fundamental power.

We have experimentally demonstrated second-harmonic generation from a GaAs/AlAs vertical cavity fabricated on a (311)B GaAs substrate. A vertical cavity offers efficient confinement of the fundamental field because highly reflective mirrors can be fabricated on both sides of the cavity. In this paper, we will present experimental results and a theoretical analysis showing that a GaAs/AlAs vertical cavity optimized both for efficient confinement of fundamental power and for quasi-phase-matching can offer efficient second-harmonic generation.

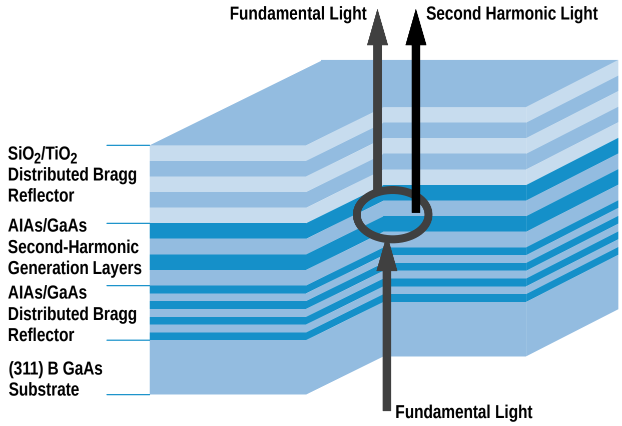

Fig. 1. Structure of the AlAs/GaAs vertical-cavity second-harmonic generator.

Structure of the Device

Fig. 1 shows the structure of the vertical-cavity second-harmonic generator, including a GaAs/AlAs distributed Bragg reflector and a TiO_2/SiO_2 distributed Bragg reflector as highly reflective mirrors. The GaAs/AlAs distributed Bragg reflector absorbs the second-harmonic power, while the TiO_2/SiO_2 distributed Bragg reflector has high transmission at the second-harmonic wavelength, so that generated light can pass through it. To generate second-harmonic power efficiently in the cavity, a periodic stack of AlAs/GaAs is incorporated for quasi-phase-matching. The conventional second-harmonic generation surface emitters demonstrated in the literature have also used a periodic structure for quasi-phase-matching whose period was equal to half a wavelength of the second harmonic.[10-12] However, our calculations indicate that the period should be a little shorter. This difference comes from the fact that while the absorption of second-harmonic power is assumed negligible in the conventional quasi-phase-matching scheme, second-harmonic power generated in the AlAs/GaAs layers is strongly absorbed, especially by the GaAs layers. From the calculated curves shown in Fig. 2, it can be seen that second-harmonic power in our quasi-phase-matched structure is generated much more efficiently than in a conventional half-wavelength quasi-phase-matched stack.

For the vertical-cavity second-harmonic generator, the second-harmonic field must be generated colinearly from the fundamental field. In zinc-blend crystals such as GaAs or AlAs, this is possible only when the substrate is oriented other than (100), such as (111), (110), or (311). A GaAs/AlAs distributed Bragg reflector (19.5 pairs) and a GaAs/AlAs stack of 19 layers were grown on a (311)B GaAs substrate by molecular beam epitaxy (MBE), resulting in good surface morphology. A TiO_2/SiO_2 distributed Bragg reflector (10 pairs) was fabricated after the MBE growth using an electron-beam evaporator and the substrate was polished to a thickness of 200 μm. We measured the total reflectivity of the device and observed a dip in the reflectivity at 984 nm, which indicated a resonance of the fundamental field in the Fabry-Perot cavity. The reflectivity of the GaAs/AlAs distributed Bragg reflector and the TiO_2/SiO_2 distributed Bragg reflector were measured to be 98.4% and 99.9% at 984 nm, respectively.

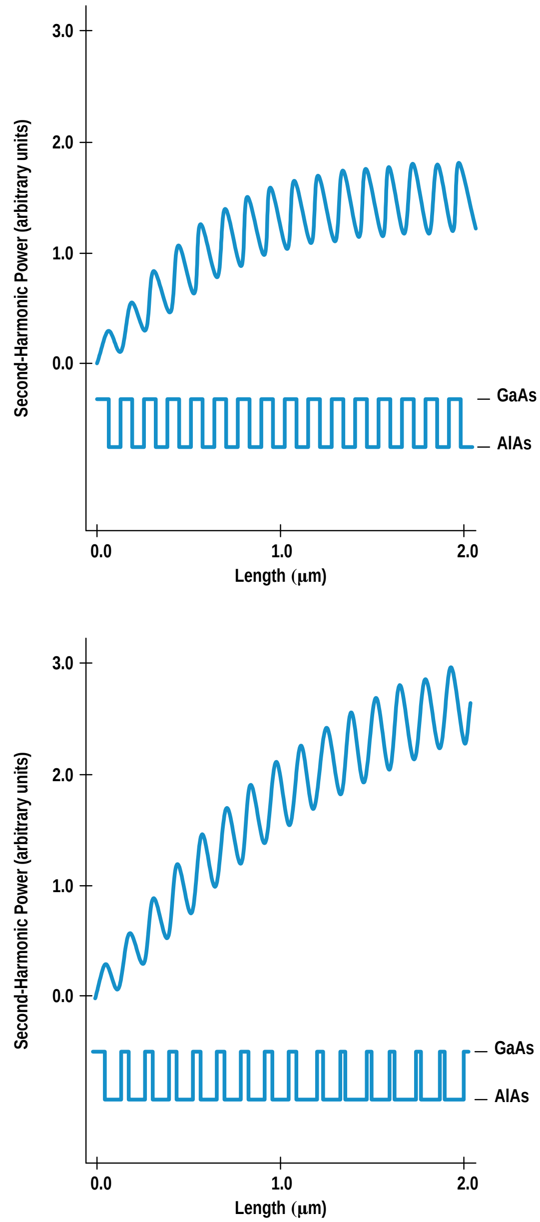

Fig. 2. Distribution of second-harmonic power in (a) a conventional half-wavelength quasi-phase-matched device and (b) a device that is quasi-phase-matched taking into account the absorption of second-harmonic power. The rectangular curves show the distribution of nonlinear coefficient in the devices. The higher and lower levels indicate GaAs and AlAs, respectively.

Results and Discussions

A frequency tunable Ti:Sapphire laser was used as a fundamental light source. The light was shot vertically through the polished GaAs substrate. We measured the second-harmonic power generated from the cavity and the fundamental power of the exiting beam. Fig. 3 shows how the second-harmonic power varies with the polarization angle of the fundamental field, in which the direction of the fundamental electric field is rotated toward the $\langle 01\overline{1} \rangle$ direction (90°) from the $\langle 2\overline{33} \rangle$ direction (0°). The points are measured data and the solid

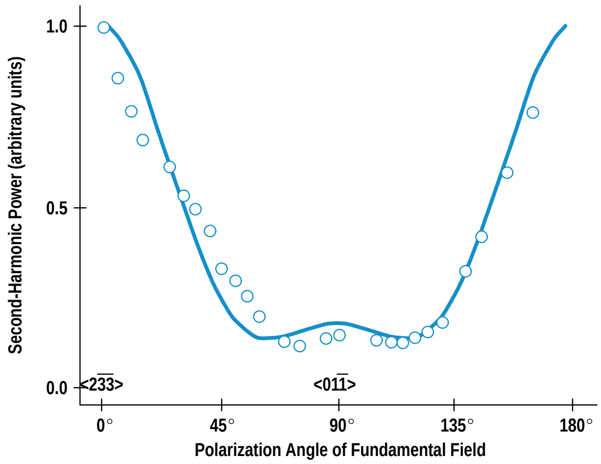

Fig. 3. Normalized second-harmonic power as a function of the polarization angle of the fundamental field. The points are measured data and the line shows the calculated values. 0° is identical to the ⟨2$\overline{3}\overline{3}$⟩ direction.

line shows the calculated values. The details of the calculations are not given here because of their complexity. However, agreement of the measurement results with the calculations indicates that the observed power is purely second-harmonic power.

Fig. 4 shows the second-harmonic power at a wavelength of 492 nm coming out of the cavity as a function of the input fundamental power at a wavelength of 984 nm, indicating that the conversion efficiency of the device is 1.4×10^{-4} %/W. The conversion efficiency of second-harmonic generation is defined as the output second-harmonic power divided by the square of the input fundamental power (the generated

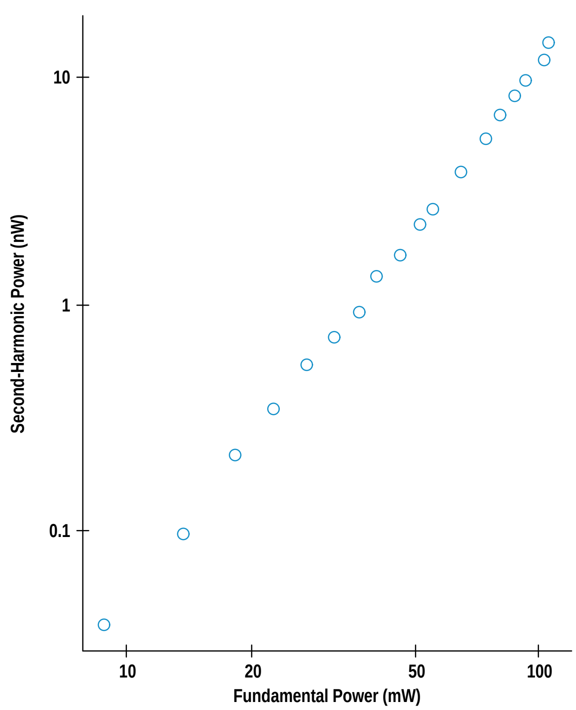

Fig. 4. Second-harmonic power coming out of the vertical cavity as a function of the input fundamental power. The wavelength of the second-harmonic power is 492 nm.

second-harmonic power is proportional to the square of the fundamental power). It is possible to increase the conversion efficiency in several ways. An efficient way is to improve the confinement of fundamental power inside the cavity. This will increase the second-harmonic power by the square of the factor by which the fundamental power in the cavity is increased, without any increase in the input fundamental power.

We found four ways to improve the conversion efficiency of our device. First, by comparing the resonant wavelength of the measurement with that of the design, we found that the actual layer thickness of the grown material was 4% smaller than the design value. As a result, our quasi-phase-matched condition was not completely satisfied. The second-harmonic power coming out of the device has been calculated both for the designed structure and for the actual structure. The calculations indicate that by making the device exactly as designed, the second-harmonic power will be increased 8.1 times compared to the device tested.

Second, the 4% reduction of the layer thickness also reduces the reflectivity of the AlAs/GaAs distributed Bragg reflector to 98.4% from the predicted value of 99.8%. This decreases the confinement of the fundamental field in the cavity. Third, the full width at half maximum (FWHM) of the Ti:Sapphire laser spectrum is 0.17 nm, which is much larger than that of the cavity, which is 0.03 nm. This causes a large part of the input fundamental light from the laser to be reflected, resulting in smaller confinement of the fundamental field in the cavity. Improvement of these second and third factors is expected to increase the fundamental power confined in the cavity to 90 times that of the present device, thereby increasing the second-harmonic power by a factor of 8.1×10^3.

Fourth, the fundamental beam from the Ti:Sapphire laser is focused on the device with a FWHM spot diameter of 18.6 μm. The conversion efficiency is proportional to the power density of the fundamental field, and would be increased 13.8 times with a fundamental beam diameter of 5 μm. Based on these considerations, we concluded that the conversion efficiency of the device would be 1.3×10^2 %/W if optimized.

Conclusions

We have demonstrated second-harmonic generation from an AlAs/GaAs vertical cavity fabricated on a (311)B GaAs substrate. We have observed a conversion efficiency of 1.4×10^{-4} %/W. We have theoretically shown that we can increase the conversion efficiency up to 1.3×10^2 %/W by optimizing both for quasi-phase-matching and for efficient confinement of the fundamental field.

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