Short Wavelength Light Sources for Digital Image Printing

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Abstract

A variety of light sources are used for printing digital data into high-quality hard copies. For traditional silver halide sensitized media, various low-power RGB light sources, such as lasers, LEDs, and CRT, are optional at present. In particular, emerging technologies of high-brightness blue and green nitride LEDs and compact blue and green SHG lasers are becoming more important as key devices for digital photo finishing area. In this paper, the technologies and physics of these devices are discussed in detail. We have developed two types of SHG light sources in Fuji. The intra-cavity SHG using bulk periodically poled crystal and the direct wavelength conversion through the periodically poled waveguide are compared. For Printing and publishing applications, high power version of compact green SHG lasers replace bulky Ar ion lasers. Further advance in nitride semiconductor devices recently has lead to near UV semiconductor lasers and high brightness UV LEDs. These Shorter wavelength devices will bring higher resolution and enable the use of short wavelength-sensitive media.

Introduction

For hybrid imaging systems where hard copies are made from digital data, the light source is a key component to enable the electronically controlled exposure of a variety of sensitized materials. For traditional silver halide materials, red, green, and blue (RGB) light sources are essential to get a pictorial color hard copy. Red light emitting diodes (LEDs) and laser diodes (LDs) are commercially available. However, compact green and blue light sources has become available very recently.

In this paper, GaN-based commercial LEDs and two types of second harmonic generation (SHG) compact solid-state lasers developed in Fuji emitting green and blue light are described. In addition, the present status and future possibility of GaN-based UV LEDs and near UV laser diodes are presented. These devices give smaller pixels and can be used with UV-sensitive media.

RGB LEDs

Prior to the commercialization of GaN-based LEDs,[1, 2] blue and green LEDs were made with low-efficient indirect bandgap materials, SiC and GaP, respectively. The external quantum efficiency of these devices was as low as 0.1 % or less although AlGaAs red LEDs showed more than 10 % external quantum efficiency and high light output of several milliwatts. The conversion efficiency has been improved by more than two orders of magnitude with realization of GaN-based LEDs because of the direct bandgap of this material. There has been a fairly long research of GaN light emitters since the first blue LEDs with the metal-insulator-semiconductor structure was demonstrated by Pankove et al. in 1972.[3] The most difficult technical barrier was to obtain highly conductive p-type GaN which is essential for making p-n junction diodes. P-type GaN was realized by activating Mg acceptors with the electron beam irradiation[4] or the thermal annealing.[5] Nakamura et al. clarified that the Mg acceptors were passivated by hydrogen atoms which was incorporated during the crystal growth of GaN. This breakthrough lead to the first production of high-brightness blue (450 nm) and blue-green (500 nm) InGaN/AlGaN LEDs in 1993. The spectrum width of these first-generation LEDs were as broad as 70-80 nm since the active layer was heavily doped with Si and Zn as luminescent centers.

The second-generation LEDs with undoped single quantum well InGaN single quantum well (SQW) active layer were developed by Nakamura et al. in 1995.[6] The efficiency and spectrum purity were improved, and consequently, both blue (450 nm, $\Delta\lambda$=20 nm) and green (525 nm, $\Delta\lambda$=30 nm) LEDs were commercialized. These devices have made it possible to control true RGB exposures using LEDs. Typical light output of blue and green LEDs is as high as 5 and 3 mW at a standard operating current of 20 mA, respectively. The chromaticity diagram shown in Fig.1 indicates that the present RGB LEDs cover the widest range in the color space, which results in the high-quality LED full color display. The relatively pure spectrum of InGaN SQW LEDs shown in Fig.2 is suited to the application of the exposure of silver halide materials. The separation of each exposure wavelength can be clearly defined. This is very important to avoid the mixture of adjacent colors.

The advantage of LED light sources is the capability of direct modulation of light and the low cost. Although high output power of several milliwatts is emitted from a device chip, the exposure power is relatively low as compared with lasers since the emitted light uniformly diverges according to the Lambert's law so that the light collection power of optics is relatively low. Therefore, the LED exposure is suitable for a compact system with smaller format. When the large format is required, the array configuration is often used to increase the throughput of the printing system by simultaneously exposing multiple pixels. The primary scan of writing spot can be done by moving a LED head. Another method of LED exposure is to use LEDs as an area illuminator and the modulation of light is carried out by a spacial light modulator such as a liquid crystal modulator.[7] When LED arrays are used, the correction of nonuniformity of light intensity and emission wavelength among different elements is essential for high-quality pictorial hard copies. Due to the semiconductor nature, the nonuniformity depends upon the ambient temperature, the driving current, and the degradation as a function of operating time. Thus, the frequent calibration is necessary.

Green and Blue Lasers

Realization of GaN-based high brightness green and blue LEDs has enabled the RGB exposure at low power levels. Lasers are more attractive with respect to their high power and diffraction-limited light beam, by which a smaller spot size and highly efficient utilization of light can be realized on the sensitized materials. However, the conventional gas laser is inconvenient to use because it is bulky and the special power supply and the cooling scheme are usually necessary. On the other hand, green and blue LDs are still at research stage and it will take at least several years to be commercialized. At present, the second harmonic generation (SHG) is the most promising method to realize compact green and blue lasers.

We have been developing two types green and blue lasers by employing SHG; that is, the intra-cavity type and waveguide type. In this section, these two SHG devices are described.

Intra-Cavity SHG

To date, bulk nonlinear crystals, such as $KNbO_3$ and KTP, have been used to generate blue or green SHG light. However, the precise control of temperature and crystal angle with respect to optical axis is required to obtain the phase matching between the fundamental light and SHG light. In addition, the photorefractive damage causes the degradation when high power SHG light is generated in these crystals. We have developed the intra-cavity SHG lasers both for green (532 nm) and blue (473 nm) light using the novel bulk periodically poled MgO-doped $LiNbO_3$ (MgO: LN) shown in Fig.3. These SHG lasers are being used in the "Frontier" photo printer.[8] In these devices, a LD (809 nm) pumps a solid state laser, which generates the fundamental laser light with λ_0. Then, the short wavelength light with $\lambda_0/2$ is generated in the nonlinear crystal of MgO: LN The quasi phase matching (QPM) between the fundamental light and second harmonic light compensates the difference in light velocities due to the wavelength dispersion of the refractive index in LN. QPM is achieved by the periodic polarization domain inversion. By employing QPM, we can

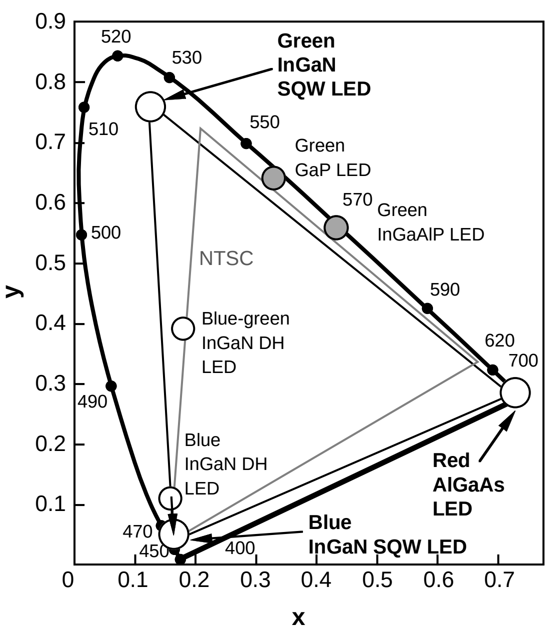

Figure 1: Chromaticity diagram in which green and blue InGaN LEDs, red AlGaAs LEDs are compared with conventional green GaP and InGaAlP LEDs and NTSC color space.

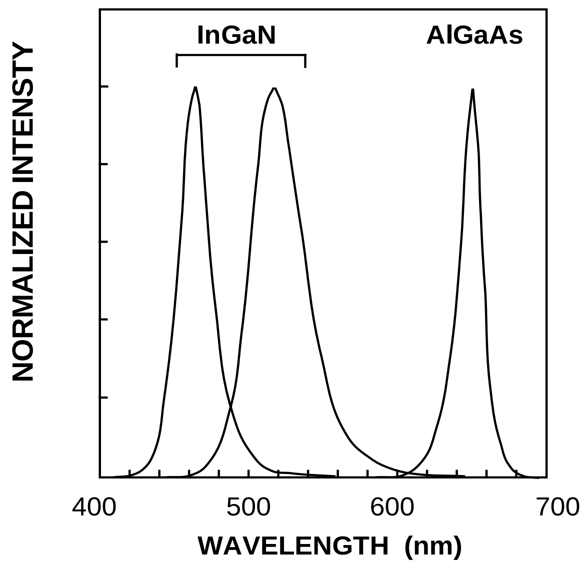

Figure 2: Emission spectra of green and blue InGaN SQW LEDs, and red AlGaAs LEDs .

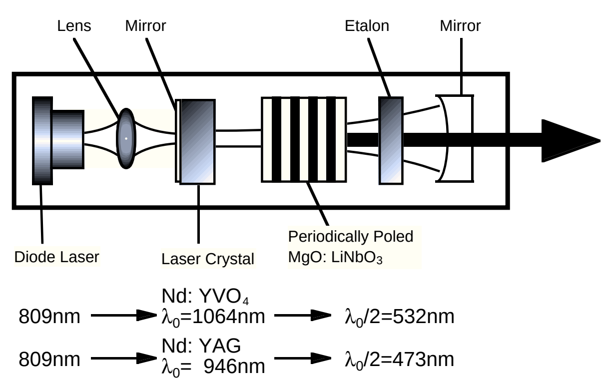

Figure 3: Schematic structure of green and blue intra-cavity SHG lasers used in the Frontier photo printer .

eliminate the crystal angle control and the precise control of temperature. Thus, only single temperature control common for a LD and MgO: LN can be used. Moreover, MgO: LN has a higher resistance to photorefractive damage than undoped LN or KTP. We have succeeded in making uniform bulk periodically poled MgO: LN for the first time by using the novel corona discharge method.[9, 10] As shown in Fig.4, a fairly high output power of 17 mW is achieved for the blue light with a LD pump power of 500 mW. For the green light, a higher power of 90 mW is obtained with the same pump power. The actual optical power used for exposing photographic papers is about 1 mW or less because of the high sensitivity of silver halide materials.

As a primary light source for exposing high quality pictorial images, stable light output and low noise are essential. The present SHG laser was designed to operate with the fundamental spatial mode with single frequency using an etalon. Thus, the stable light output is maintained even with changing the ambient temperature for a long period of time with the use of automatic power control. The spatially isotropic and almost Gaussian beam with M^2 of 1.04 - 1.05 is obtained. Due to the advantages of periodically poled MgO: LN described above, high-quality beam is maintained within the temperature range of 10-45 °C for a long period of operating time without noticeable degradation. We have developed the pumping LD with the Al-free active region, which ensures high reliability with minimal possibility of sudden failure.[11] The light output of intra-cavity SHG laser cannot be modulated with a high frequency since the excited state of solid state laser crystal has a long lifetime of the order of µsec. An external light modulator, such as an acousto-optic modulator, is used for high-speed modulation.[8]

Waveguide SHG

In the waveguide SHG device, the periodic domain inversion is formed along the optical waveguide fabricated in the nonlinear crystal, such as LN and $LiTaO_3$ (LT) as shown in Fig.5. The input laser light with λ_0 is directly converted to $\lambda_0/2$ during the propagation through the waveguide, which supports the fundamental transverse mode. When combined with a single frequency LD as an excitation source, the waveguide SHG is much simpler than the intra-cavity SHG. In addition, the strong confinement of the fundamental light in the waveguide results in the high conversion efficiency even with single path of the excitation light without an optical cavity.

To date, the most of waveguide SHG is made with using Z-cut substrates such as LN and LT since the domain inversion occurs along the Z axis so that the deeper inversion is easily obtained. The deep domain inversion is very important to get high conversion efficiency of SHG because the overlap between the fundamental propagating light and the domain inverted region determines the conversion efficiency. However, only the TM mode is supported in this configuration, and thus, the LD light with the TE mode cannot be directly coupled to the waveguide. We have recently fabricated TE-mode waveguide SHG device using X-cut and Y-cut MgO: LN substrates.[12] In order to increase the depth of the domain inversion, the substrate orientation is inclined by 3° from the nominal orientation.[13] As a result, the depth of domain inversion was increased to 2.5 µm, which is 2.5 times deeper than that formed on the nominally X- and Y-cut substrates. The

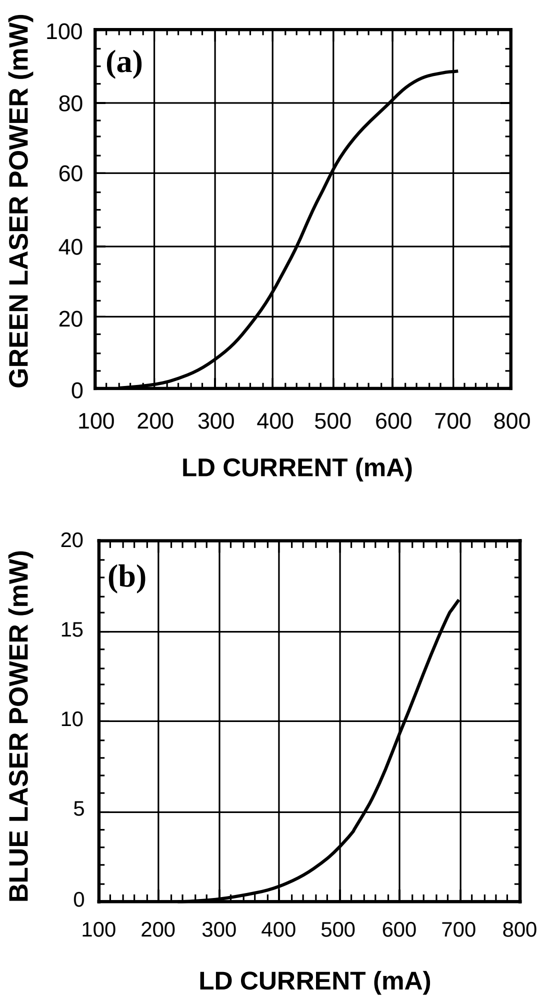

Figure 4: Light output of intra-cavity (a) green and (b) blue SHG lasers as a function of laser diode driving current.

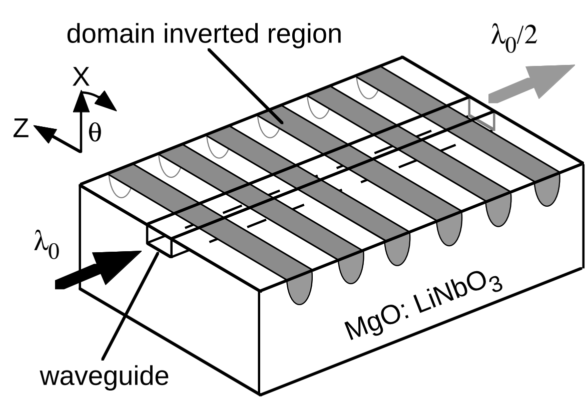

Figure 5: Schematic structure of waveguide-type SHG device using x-cut MgO: $LiNbO_3$.

domain inversion was formed by applying electric field with using segmented electrodes. A channel waveguide was made by the proton exchange method at 160 °C with pyrophosphoric acid. As shown in Fig.6, the blue SHG light (475 nm) of 37 mW was achieved at 107 mW fundamental light (950nm) from a tunable external cavity LD. The waveguide SHG device has a capability of the direct modulation by modulating the diode laser. Further development will be necessary for making a compact module using a conventional LD.

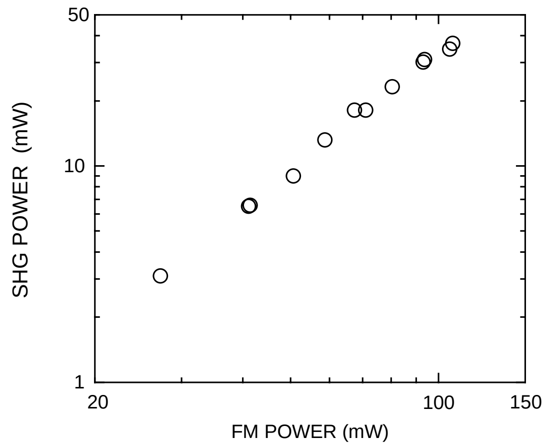

Figure 6: SHG light (475 nm) output as a function of power of fundamental light (950 nm) in waveguide SHG device fabricated on 3°-off X-cut MgO: LN.

UV Light Emitters

The further progress in GaN-based light emitter has lead to the successful demonstration of long-life short wavelength LDs with the wavelength range of 400-410 nm.[14] The estimated lifetime of devices operated at 2 mW exceeds 10,000 hours at RT. Nichia Chemical Co. announced that commercial samples would be delivered by the end of 1998. The emission wavelength of GaN-based devices can be controlled by changing the In composition of InGaN active layer; the more In content leads to the longer wavelength. However, the increase in the In composition results in the degradation of crystalline quality of InGaN because of the lattice mismatch between InGaN active layer and surrounding GaN and the inhomogeneous In composition of InGaN. Thus, the longer wavelength LDs in the blue-green region are very difficult to make and have not been demonstrated yet. This difficulty is represented by the broader luminescence spectrum of LEDs with increasing the In composition as shown in Fig.2. With regard to LEDs, the high brightness UV LEDs were reported emitting at 371 nm with the spectrum width of 8.6 nm.[15] The output power was 5 mW. These UV light sources can be used for the systems in combination with the UV sensitive materials in future.

Summary

A variety of light sources became available in recent years for hybrid imaging systems. In particular, the realization of RGB LEDs and RGB lasers has made it possible to use conventional silver halide photographic papers in digital printers, which produce high quality pictorial hard copies from various storage media and from the network with the full use of digital technologies. This good combination of the electronics and the chemical imaging technologies will open up the new horizon of the imaging world.

References

1. J.I.Pankove and T.D.Moustakas (ed.), *Gallium Nitride (GaN) I*, Semiconductors and Semimetals, Vol.50, Academic, San Diego (1997).
2. S.Nakamura and G.Fasol, *The Blue Laser Diodes: GaN Based Light Emitters and Lasers*, Springer, Berlin (1997).
3. J.I.Pankove, E.A.Miller, and J.E.Berkeyheiser, J. Luminescence **5**, 84 (1972).
4. H. Amano, M.Kito, K.Hiramatsu, and I.Akasaki, Jpn. J. Appl. Phys. **28**, L2112 (1989).
5. S.Nakamura, N.Iwasa, M.Senoh and T.Mukai, Jpn. J. Appl. Phys. **31**, 1258 (1992).
6. S.Nakamura, M.Senoh, N.Iwasa, and S.Nagahama, Jpn. J. Appl. Phys. **34**, L797 (1995).
7. T.Narita and S.Tahara, IS&T's 9th Symposium on Photofinishing Technology, Feb. 18-21 (1996).
8. Y.Morimoto, Proc. IS&T/OSA Optics & Imaging in the Information Age, p.379 (1996).
9. A.Harada and Y.Nihei, Appl. Phys. Lett. **69**, 2629 (1996).
10. A.Harada, Y.Nihei, Y.Okazaki, and H.Hyuga, Opt. Lett. **22**, 805 (1997).
11. T.Fukunaga, M.Wada, H.Asano, and T.Hayakawa, Jpn. J. Appl. Phys. **34**, L1175 (1995).
12. S.Sonoda, I.Tsuruma, and M.Hatori, Appl. Phys. Lett. **70**, 3078 (1997).
13. S.Sonoda, I.Tsuruma, and M.Hatori, Appl. Phys. Lett. **71**, 3048 (1997).
14. S.Nakamura, M.Senoh, S.Nagahama, N.Iwasa, T.Yamada, T.Matsushita, H.Kiyoku, Y.Sugimoto, T.Kozaki, H.Umemoto, M.Sano, and K.Chocho, Proc. 2nd Int. Conf. on Nitride Semicond. S-1, p.444 (1997).
15. T.Mukai, D.Morita, and S.Nakamura, Proc. 2nd Int. Conf. on Nitride Semicond. LN-9, p.516 (1997).