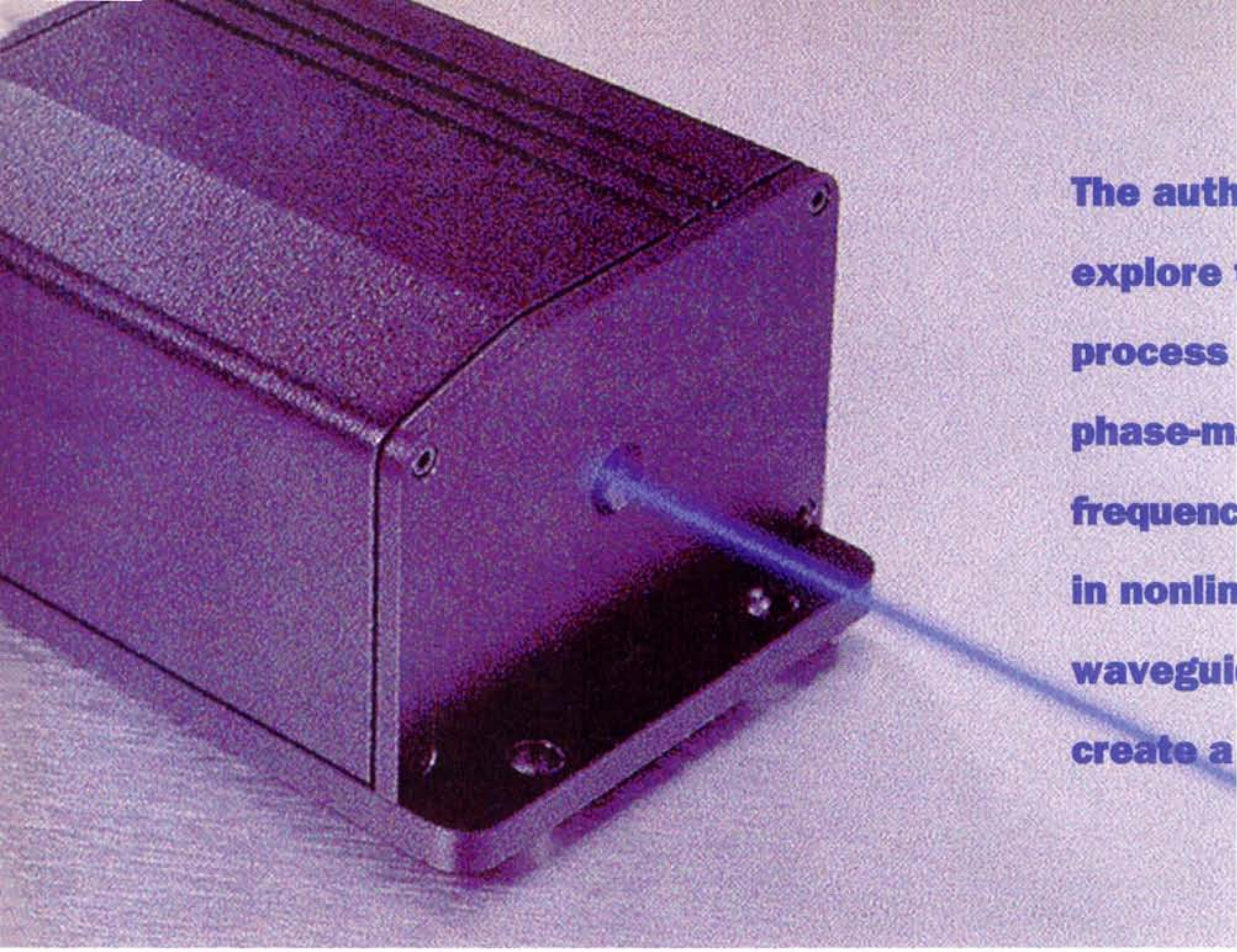

**The authors explore the process of quasi-phase-matched frequency doubling in nonlinear waveguides to create a blue laser.**

A compact blue laser source based on QPM nonlinear waveguide technology.

# Nonlinear Waveguides on the Way to the Marketplace

By Jonas Webjörn, Derek Nam, Sabeur Siala, and Robert Waarts

Advantages of high efficiency, compact size, high reliability, and low cost mean laser diodes are used in many different applications. While reliable laser sources are available from 630–2000 nm, many applications require wavelengths outside this range. For instance, blue-green sources are required in such applications as optical data storage, color printing, projection displays, and medicine. Present blue-green sources are based mostly on gas lasers or resonant frequency converted solid-state lasers which are inefficient, complex, and/or operate over a limited wavelength range. A potential blue-green source is being explored through quasi-phase-matched (QPM) of nonlinear waveguides.

Nonlinear waveguides offer a means of direct


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and efficient frequency doubling of laser diodes at the currently available 100 mW to 1 W power levels. An additional advantage of nonlinear waveguides is that, by using QPM, they provide frequency doubling over the entire transparency range of the nonlinear crystals, from approximately 350 nm to 4.5 μm. Recent demonstrations of visible laser sources based on nonlinear waveguides include, among others, 25 mW at 425 nm, 100 mW at 550 nm, and a compact turnkey, 2-mW output power, 425-nm prototype laser.1

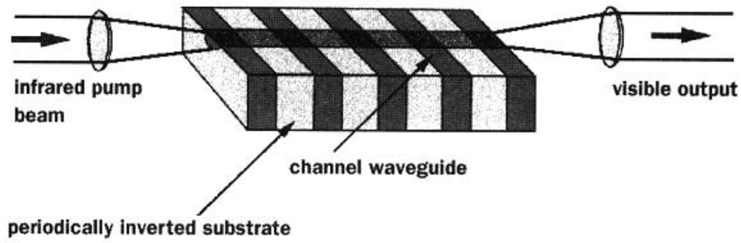


**Figure 1.** Schematic of a quasi-phase-matching channel waveguide.

## QPM nonlinear waveguides

The concept of frequency doubling in a nonlinear waveguide is shown schematically in Figure 1. The input light is focused into a single-mode waveguide that is formed in a nonlinear substrate. The infrared pump light is confined to the small area of the waveguide, along its full length. The propagating infrared wave induces a polarization in the material that oscillates at twice the optical frequency of the infrared wave. Therefore, every part of the waveguide acts as a local emitter of blue light. Since it is a nonlinear material, the fraction of pump power coupled to the oscillation at the second harmonic frequency gets larger for stronger intensity input light. Thus, confining the input light to a small 3-5 μm single-mode waveguide results in a more efficient process than focusing the light in a bulk nonlinear crystal with typical spot sizes of tens of microns over a similar 1-cm interaction length. As a result, efficient doubling in nonlinear waveguides is achieved at power levels less than 100 mW—well within the range of laser diodes. Frequency doubling in bulk nonlinear crystals, on the other hand, requires input powers in the range of 20–1000 W.

An essential requirement for efficient conversion in any nonlinear material is that the microscopic emitters emit the generated blue light in phase along the direction of propagation of the light. Since the phase of the local blue oscillation is set by the phase of the infrared pump light, the requirement that all blue-emitting parts of the waveguide be in phase translates into the requirement that the blue and the infrared optical waves experience equal refractive indexes. Normally, dispersion causes a difference in index, *i.e.*, a phase-mismatch for the optical waves. Several ways to cancel this mismatch in nonlinear waveguides have been demonstrated.[2] These include matching different polarizations in birefringent crystals and various ways of matching the infrared light to higher order blue modes, or even blue light that is not confined in the waveguide. However, these methods have a limited wavelength range and some give an output beam which does not have a proper Gaussian profile.

QPM is based on accepting the local phase mismatch and inverting the crystal orientation of those regions that are 180° out of phase. This inversion phase shifts the local blue oscillation 180°, bringing the regions (domains) back into constructive interference. For example, the generation of blue light requires a domain inversion period with a period in the range of 2–4 μm. The challenge is how to create these regions of opposite polarity, *i.e.*, how to perform domain inversion.

QPM has important advantages over other phase-matching methods. The main advantage is that QPM can be achieved at any wavelength within the transparency range of the nonlinear material, simply by the correct choice of the domain inversion period. Consequently, when combined with laser diodes, any wavelength in the visible spectrum may be generated. Furthermore, QPM allows a free choice of polarization of the interacting light waves, permitting efficient nonlinear interaction between waves that all have extraordinary polarization. This results in a greater than 10 times more efficient conversion compared to other, more conventional methods of achieving phase matching.

## Nonlinear waveguide demonstrations

There are many materials that have a large optical nonlinearity, but QPM, as well as waveguide fabrication, has only been demonstrated in some. To date, the more successful materials have been the two sister materials, lithium niobate and lithium tantalate, and the family of KTP (potassium-titanyl-phosphate) and its isomorphs.

Currently, the most successful waveguide fabrication method in nonlinear crystals is based on ion exchange. In this process, the waveguide is patterned in a mask layer on the surface of the crystal substrate, which is then immersed in a melt containing the ion to be exchanged. An ion in the crystal diffuses to the melt and an ion from the melt diffuses into the crystal. This exchange results in an increase in the index of refraction. For example, in KTP, rubidium ions replace potassium ions, and in lithium niobate and lithium tantalate, hydrogen ions (protons) replace lithium ions. In lithium niobate and lithium tantalate, the process is usually referred to as a proton-exchange.

While the ability to form waveguides narrows down the list of potential nonlinear crystals, the further requirement that the material should lend itself to periodic domain inversion narrows down the list even more. The nonlinear materials that are used are the so-called ferroelectrics. This means that they have a permanent electric polarization in analogy with ferromagnets, which have a permanent magnetic polarization. The electric polarization can be switched between at least two different directions. Lithium niobate can be used as an example of the actual physical mechanisms involved in the domain inversion. The crystal structure of lithium niobate consists of a hexagonal close-packed oxygen lattice with lithium and niobium ions distributed between the oxygen planes. Looking at the structure from the side, the order of the metal ions is vacancy, lithium, niobium, vacancy, lithium, niobium, and so on. Domain inversion corresponds to shifting the lithium ion across an oxygen-plane so that the order is now lithium, vacancy, niobium, lithium, vacancy, niobium, and so on, resulting in a reversal of the polarity of the crystal.

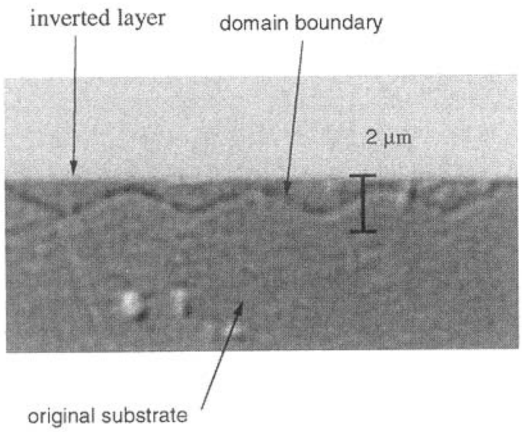


**Figure 2.** Microscopic picture of the periodic domain inversion in Ti-diffused lithium niobate.

As we discuss below, the poling processes that have been used to induce domain inversion include diffusion and electric-field poling. The diffusion processes are based on the fact that a concentration gradient causes a corresponding electric field. When a substrate is cooled down after a quick treatment in a diffusion furnace, domain inversion appears in regions where a dopant has been introduced. E-field poling uses the fact that a strong electric field also reorients the ions in the crystal. Periodicity is achieved either through the use of periodic electrodes or by periodically inhibiting poling with a chemical patterning of the substrate of the crystal. Three examples of QPM waveguide fabrication are given below. In two of the processes, the domain inversion is performed as a first step and then the waveguides are introduced. The third example (KTP) is a one-step process, which both increases the refractive index and induces domain inversion.

## QPM waveguide fabrication

*Ti-diffused lithium niobate*

In Ti-diffused lithium niobate based nonlinear waveguides, a thin layer of titanium is deposited on the c+ face of the substrate and patterned into a grating that has the period required for QPM at the desired wavelength.[3] The substrate is then given a quick heat-treatment—above 1000°C. As illustrated in Figure 2, the domains that result from the periodic Ti-diffusion have a triangular profile that follows the diffusion profile of titanium in the lithium niobate. After the titanium-induced periodic domain inversion, a waveguide is fabricated by an annealed proton exchange process. Due to the zig-zag shape of the domain boundary, only part of the infrared and blue waves that propagate in the waveguide will experience a periodic medium. The fabrication process has to be controlled very carefully so that the domain boundary ends up just the depth where the blue and infrared waves have their maximum intensity. Once that is achieved, however, this process gives quite efficient devices. Figure 3 shows the measured output power in the blue as a function of the input wavelength.

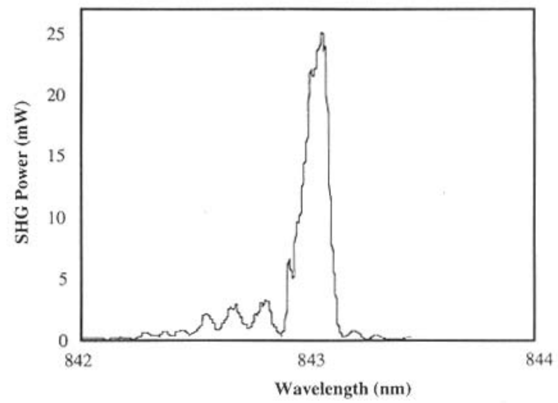


**Figure 3.** Blue power as a function of infrared pump wavelength in a lithium niobate waveguide.

A maximum output power of 25 mW at 421.5 nm is obtained at around 843-nm input wavelength. The width of the phase matching peak is approximately 0.15 nm, which is less than twice the theoretical width and indicates that the high uniformity of the waveguide allows the full 1-cm length to take part in the conversion.

*E-field poled lithium niobate*

In E-field poled lithium niobate, the periodic domains are induced by the application of a very strong electric field, above 20 kV/mm.[4] The difference from the diffusion-based processes is that here the inversion occurs very rapidly, during a few milliseconds, and that it is performed at room temperature. In the diffusion-based processes the domain boundaries (or domain walls) can take any orientation that is favored by the crystal structure. Any surface charge at the domain walls due to the opposite polarity of the domains can be compensated by free charge inside the crystal drifting to the wall. In E-field poling on the other hand, the resistivity of the material is high enough to prevent any free charge from compensating the surface charge. Thus the domain walls have to take the minimum-energy orientation parallel to the polar axis. In device fabrication, the domains become almost perfectly perpendicular to the substrate, which is ideal for QPM applications.[5] Figure 4 shows the green output power generated in an E-field poled lithium niobate waveguide as function of input power around 1100 nm. A maximum output power of 100 mW is obtained for 400 mW of pump power coupled into the waveguide, corresponding to 25% optical-to-optical efficiency.

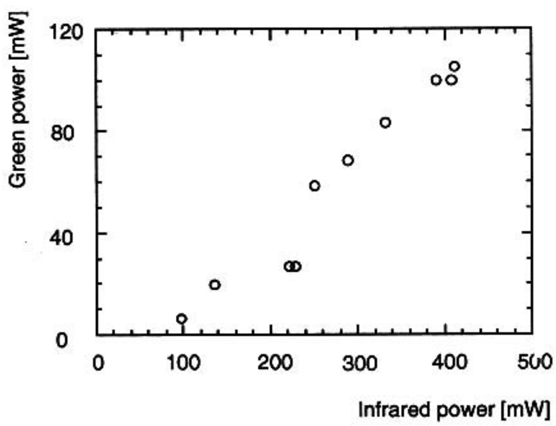


**Figure 4.** Green power vs. infrared pump power in an E-field poled lithium niobate waveguide.

*Rb-exchanged KTP*

Rb-exchanged KTP is a one-step process where rubidium ions are exchanged for potassium ions.[6] The exchange causes both an index increase and domain inversion. The crystal structure is such that the diffusion only appears along "channels" parallel to the crystallographic c-axis. This produces nearly perfect domain walls perpendicular to the surface, with the domains only extending to the depth of the ion exchange profile. To achieve periodic domain inversion, the mask pattern consists of a row of open dots—a "string of pearls." It has been experimentally determined that the periodic index profile can be used instead of a continuous index profile without any significant increase in optical loss. Rb-exchanged KTP waveguides were used for some of the earliest successful demonstrations of generation of several milliwatts of blue output power. More recently, the KTP processing has also been extended to a two-step process based on E-field poling.[7]

## Blue laser module

A compact and robust blue laser module based on frequency doubling of a laser diode source in a QPM channel waveguide has been developed. These components are packaged together in a standard-type telecom package with the dimensions 21 mm × 13 mm × 9 mm. An output power up to above 4 mW has been demonstrated for wavelengths from 425 nm to 455 nm. A noise figure of –140 dB/Hz has been measured in the range from DC to MHz. This device has also been integrated into a compact turnkey system, shown in the opening image on page 16, that includes drive electronics. Measurements of the beam quality of the blue output from this module include 98% ellipticity and 1.4 × 1.2 $M^2$ numbers. As mentioned earlier, a main advantage of this technology is that any output wavelength can be obtained throughout the visible spectrum down to the near ultraviolet.[8]

## Conclusions

QPM nonlinear waveguides permit efficient frequency doubling of laser diodes over the entire visible wavelength range. The waveguides have been demonstrated in various materials with output powers in the visible of up to 100 mW. Compact devices have been fabricated with several milliwatt output power. These devices will compete on the market with other visible laser sources, including air-cooled argon lasers and frequency doubled solid-state lasers. The latter have been demonstrated in the laboratory and may be introduced commercially in the near future. Some of the advantages of QPM technology over other technologies include wavelength flexibility, high efficiency, and small size. In addition, since the technology is based on direct frequency doubling of laser diodes, many of the advantages of laser diodes, such as direct modulation and low noise, can be obtained from the QPM waveguide based devices. In the long term, direct-emitting blue and green semiconductor technologies will almost certainly provide the much sought-after rugged blue-green lasers. Presently, however, these lasers are relatively immature when compared to current commercially available infrared diode lasers.

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