where $\Psi = \xi_c'^2 - \xi_c''^2$ and $\phi = 2\xi_c' \xi_c''$. Since, for a chiral material, there exists an extra complex parameter (ξ_c) in addition to the usual parameters (ε and μ) of conventional materials, electromagnetic properties of such a medium can be controlled and tailored with increased flexibility. From a mathematical point of view, one might anticipate the usefulness of chiral material for zero reflectivity by noting that extra degrees of freedom are available for impedance matching as compared to the achiral case. From a more physical viewpoint, we note that the chirality admittance fine-tunes the deficit between the permeability and permittivity ratios which would be optimum for matching in conventional materials. Explicitly, ξ_c' and ξ_c'' can remove this difference in value between ε' and μ', and ε'' and μ'' inherent in today's achiral materials, and consequently achieve perfect impedance matching. Further, we note that the above result is independent of the polarisation of the incident wave and the sign of the chirality admittance indicating the handedness of the medium. The chiral material whose constitutive parameters satisfy condition expr. 4 we name Chirosorb™.

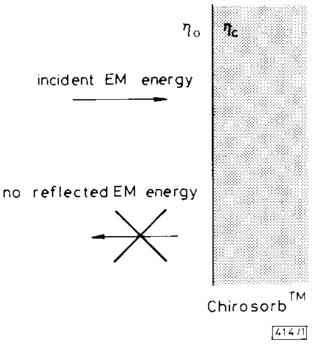

Fig. 1 *Chirosorb™, as an 'invisible' material, reflects no electromagnetic energy*

The results embodied in eqns. 3 and 4 are deceptively simple because they have been cast into the form used for the achiral case. However, we reiterate that these results come from the solution of the complete boundary-value problem displayed in Fig. 1, and that all of the chiral information and complexity has been embedded in the chirality impedance η_c.

Nowadays, conventional materials used for RCS reduction are composite materials that are in general lossy and anisotropic. The anisotropy poses problems in the design, manufacture and application of such materials. In addition, the complex electromagnetic parameters of these materials may exhibit extreme frequency sensitivity. Chirosorb™, owing to the above advantages, is a strong candidate for effective RCS management.

One way of making Chirosorb™ is by embedding randomly oriented identical chiral microstructures, such as microhelices, in an isotropic host medium. Geometric dimensions and density of the chiral microstructures will determine constitutive parameters (ξ_c, ε, μ) of the chiral medium and can be tailored to satisfy eqn. 4, as will be detailed in forthcoming papers.

In summary, we have introduced a novel synthetic material named Chirosorb™, which is invisible to electromagnetic energy and has properties which are independent of polarisation in the backscatter direction. The introduction of electromagnetic chirality to the problem of RCS reduction has added extra flexibility through the complex chirality admittance ξ_c. We have shown that by properly choosing the chirality admittance, one can achieve zero reflectivity.

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SECOND-HARMONIC GENERATION OF GREEN LIGHT IN PERIODICALLY POLED PLANAR LITHIUM NIOBATE WAVEGUIDE

Indexing terms: Optics, Optical waveguides, Integrated optics, Nonlinear optics

A periodically poled, planar waveguide in lithium niobate was used to generate 532 nm radiation at room temperature by continuous-wave frequency-doubling with a conversion efficiency of 5% per W cm^2. Quasi-phase-matching allowed generation of the second harmonic using the d_{33} nonlinear coefficient.

Introduction: Frequency doubling in a lithium niobate optical waveguide is an attractive method for generating coherent visible radiation. To date, such devices have involved birefringent phase-matching, modal dispersion or the Cerenkov effect.[1,2] An alternative method for compensating refractive-index dispersion in nonlinear optical interactions is quasi-phase-matching (QPM).[3] Periodic reversal of the sign of the nonlinear coefficient of the material at odd integer multiples of the coherence length prevents the accumulation of phase mismatch between the interacting waves. QPM can be used for nonlinear interactions which cannot be birefringently phase-matched owing to the material, wavelengths or nonlinear coefficients involved. In the present work, QPM enables the use of the d_{33} coefficient for an interaction between z-polarised fields in lithium niobate. The use of d_{33} is desirable because it is seven times larger than the d_{31} coefficient used in birefringently phase-matched interactions.

Periodic reversal of the nonlinear coefficient for quasi-phase-matched bulk interactions has been accomplished using stacks of oriented plates,[4,5] rotationally twinned layers,[6] periodically poled crystals,[7,8] and more recently periodically poled single-crystal fibres.[9,10,*] The prospect of a guided-wave device using QPM is attractive because it combines the flexibility of QPM with the efficiency of waveguide interactions.[11,12]

We report a technique for patterning the nonlinear coefficient at the surface of a lithium niobate substrate, and quasi-phase-matched frequency-doubling in a waveguide in such a substrate. The high conversion efficiency resulting from the use of the d_{33} coefficient in a guided-wave geometry is demonstrated in a device fabricated with commonly used materials and processes.

Poling process: The signs of the nonlinear coefficients in lithium niobate are linked to the direction of the spontaneous ferroelectric polarisation. Periodic reversal of the ferroelectric polarisation in the crystal (periodic poling) thus periodically reverses the signs of the nonlinear coefficients. It is known that titanium diffusion into the $+c$ face of a lithium niobate wafer causes ferroelectric domain reversal at the surface of the wafer.[13,14] We employ this effect to create patterned domains at the surface of a lithium niobate substrate. Liftoff lithography is used to pattern a Ti layer. A subsequent heat treatment in the 1000–1100°C range produces domain reversal in the patterned areas. We have produced domain patterns with periods ranging from 5 to 50 μm. Fig. 1 shows a periodic domain structure created by patterned Ti indiffusion.

Device technology: For the initial optical demonstration, the $+c$ face of a 0·5 mm-thick lithium niobate substrate was patterned with four Ti gratings, each about 1 mm long, with

[*] MAGEL, G. A., FEJER, M. M., and BYER, R. L.: to be published

periods ranging from 15 to 22 μm. The gratings were comprised of Ti lines 4 μm wide and 5 nm thick. The grating periods were chosen so the resulting domains would be about three coherence lengths long for doubling 1·06 μm radiation. The gratings were arranged so that a light beam would traverse all four gratings before exiting. The heat treatment consisted of a 2 h ramp-up from room temperature to 1100°C, and a 30 min soak at 1100°C, after which the oven was turned off and allowed to cool to room temperature. The oven had an initial cooling rate of 8 K/min. To prevent outdiffusion of lithium oxide from the sample during the poling process, the substrate was placed in a closed alumina boat filled with congruent lithium niobate powder. After the heat treatment, we made a planar annealed proton-exchange waveguide in the substrate.[15] This involved a 30 min soak in pure benzoic acid at 200°C followed by a 4 h anneal in flowing oxygen at 350°C. The resulting waveguide had a single TM mode at 1·06 μm.

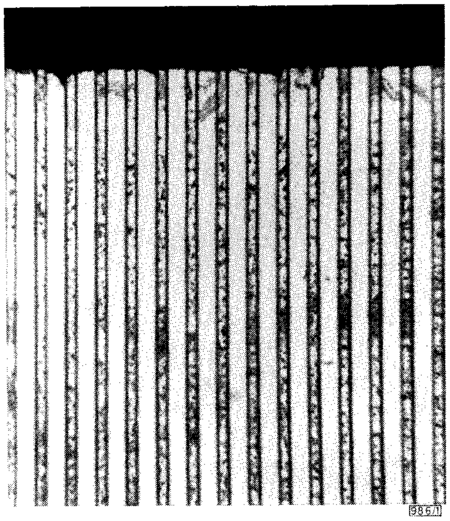

Fig. 1 *Periodic ferroelectric domains on c-face of lithium niobate wafer revealed by etching with HF acid*

Period of pattern is 10 μm

Experiment: Input and output coupling was accomplished with rutile prisms. An 8 cm focal length cylindrical lens at the input focused the beam in the plane of the waveguide. With 1 mW of CW power at 1·06 μm measured at the output of the waveguide, we observed the generation of 0·5 nW of 532 nm radiation. Both the fundamental and harmonic waves had the proper polarisation for operation using d_{33}. The conversion efficiency of the device was about 5% per $W cm^2$.

We modelled the waveguide as a step-index guide with a refractive index increase of 0·003. Estimating the depth of the waveguide to be in the range 4–7 μm, we calculated theoretical conversion efficiencies ranging from 7 to 10% per $W cm^2$, in reasonable agreement with the experimental value. From these values we calculate that the observed second harmonic power is roughly 1500 times larger than what one would see if the interaction were not phase-matched.

We are pursuing techniques to improve the conversion efficiency of the device. Two orders of magnitude can be gained by increasing the grating size from 1 mm to 1 cm. A first-order grating offers a ninefold increase in efficiency over that provided by the current third-order grating, and a further substantial improvement can be obtained with a channel rather than a planar waveguide. Scaling the observed conversion efficiency of 5% per $W cm^2$ with these improvements implies that mW levels of second harmonic could be generated from tens of mW of input fundamental power. While we are currently working with 1·06 μm fundamental radiation, the application of this QPM technique to the doubling of diode lasers offers an attractive method for generating coherent blue light.

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EXTREMELY NARROW LINEWIDTH (~1 MHz) AND HIGH-POWER DFB LASERS GROWN BY MOVPE

Indexing terms: Semiconductor lasers, Epitaxy

A suitable structure of narrow linewidth DFB laser is studied experimentally. By thinning the active layer to around 0·07 μm, controlling κL to 1·0, and improving the geometrical uniformity of active region, the linewidth less than 1 MHz is achieved at an output power of around 20 mW in 1·55 μm DFB lasers with 1·2 mm long cavity length.

Introduction: In coherent optical transmission systems, a narrow spectral linewidth DFB laser diode is indispensable. In particular, a narrow spectral linewidth oscillation at high