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DBR waveguide laser in erbium-diffusion-doped $LiNbO_3$

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Indexing terms: Distributed Bragg reflector lasers, Crystal waveguide lasers, Lithium niobate

The first integrated optical DBR waveguide laser with dry-etched Bragg grating (345 nm period) is demonstrated in Er-diffusion-doped *Z*-cut $LiNbO_3$ with Ti-diffused waveguide. Three different resonator configurations have been investigated. The best device has a threshold of 40mW coupled pump power (λ_p = 1484nm) and emits up to 2mW CW output power at λ_s = 1531nm with a typical bandwidth of 3.6GHz.

Introduction: One of the key components for applications in optical communication and instrumentation is an integrable, narrow band, fixed frequency light source. In semiconductors, distributed feedback (DFB) and distributed bragg reflector (DBR) lasers have been developed which satisfy most of the requirements. In $LiNbO_3$, however, up to now free running lasers [1], modelocked lasers [2] and tunable lasers [3] with erbium-doped Ti:$LiNbO_3$ waveguides have been reported with dielectric end face mirrors only. Despite the attractive properties of these lasers, narrow bandwidth operation and integration with further components on the same chip is difficult. Therefore, we developed the first DBR waveguide laser in erbium-diffusion-doped $LiNbO_3$. This Letter reports the fabrication and operation of a DBR laser with three different resonator configurations.

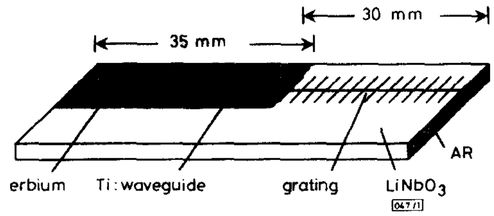

Fig. 1 *Schematic diagram of Z-cut Ti:Er:$LiNbO_3$ DBR waveguide laser*

Resonator configurations: Fig. 1 shows a schematic diagram of the laser of 60mm overall length. It consists of a titanium-indiffused monomode waveguide in *Z*-cut, *Y*-propagating $LiNbO_3$ with a gain section of 35mm length, defined by local erbium doping. The laser cavity is formed by an end face mirror on the left and distributed reflector on the right. The latter is a first order Bragg grating of 345.5nm period and 30mm length, etched into the surface of the undoped waveguide. The resulting narrowband reflection for σ polarised optical modes (TE) matches the gain peak of Er:$LiNbO_3$ at λ = 1531nm. The right end face of the sample is antireflection (AR) coated. Three resonator configurations with different end face mirrors on the left have been investigated:

(i) The end face is uncoated resulting in a broadband reflectivity of 14.3% determined by the index difference between $LiNbO_3$ and air.

(ii) The end face is coated with a broadband dielectric mirror of 98% reflectivity for both pump and signal wave.

(iii) The end face is coated with a dichroic mirror of 90% reflectivity for the signal, but of ~85% transmittivity for the pump.

Laser fabrication: The fabrication of the laser essentially consists of four steps: planar erbium-diffusion doping of the gain section, waveguide definition, DBR grating fabrication, and dielectric coating deposition.

(*a*) A vacuum deposited Er_2O_3 film of 28nm thickness was indiffused at a temperature of 1130°C for 100h resulting in a Gaussian-like doping profile of 5.5μm depth and a surface concentration of $1.45 \times 10^{20} cm^{-1}$ [4].

(*b*) 7μm wide, 95nm thick titanium stripes were photolithographically defined on the $LiNbO_3$ surface and subsequently indiffused at 1030°C for 9h yielding monomode waveguides for $\lambda \simeq 1.5$μm.

(*c*) First order DBR gratings of 345.5nm period were fabricated using dry etching techniques. A protective Cr layer was sputtered onto the sample surface and photolithographically patterned to define openings for the grating areas. A layered structure of heat resistant polyimide, sputtered Cr etch-stop, dyed polyimide AR coating (to suppress backreflections), and photoresist was then deposited. The grating was holographically exposed in the resist. Rectangular grating mask line profiles were obtained by Cr shadow evaporation onto the resist relief, O_2 gas reactive ion etching (RIE) down to the Cr stop layer, opening of this layer by SF_6 gas RIE and a final O_2 gas RIE down to the crystal surface. The polyimide/metal mask obtained was then transferred into the $LiNbO_3$ to a depth of ~240nm using an SF_6 gas RIE process. A more detailed description of the grating processing can be found in [5]. An SEM micrograph of the etched grating is shown in Fig. 2.

(*d*) The end faces of the sample were coated using an ion beam assisted evaporation technique. A single quarter-wave SiO_2 layer was vacuum deposited onto the right end face as an AR coating. The left end face remained uncoated or was coated with a stack of 14 or 18 layers of TiO_2 and SiO_2 to obtain a broadband or dichroic mirror, respectively.

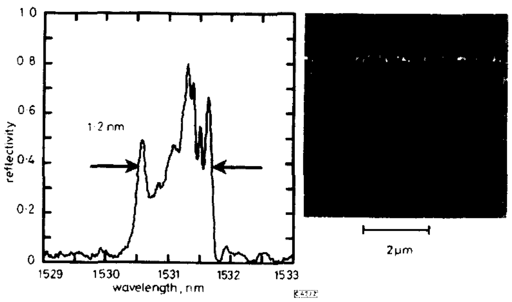

Fig. 2 *TE reflectivity of 30mm long Bragg-grating against wavelength and SEM micrograph of etched grating on top of waveguide*

Characterisation of passive device: The titanium-diffused optical channel waveguides are singlemode in the wavelength regime around 1.5µm. σ-polarised modes of $5.7 \times 4.0\ \mu m^2$ extension (horizontal half width × vertical half width) are guided with scattering losses as low as 0.07 dB/cm. The in-diffused erbium doping is responsible for absorption coefficients of $\alpha(1484nm) = 1.8dB/cm$ and $\alpha(1531nm) = 6.7dB/cm$. The reflection characteristics of the grating structures (Fig. 2) were measured using the broadband fluorescence of an erbium-doped fibre.

The halfwidth of 1.2nm is much broader than expected theoretically and measured with other samples [5]. An ideal, chirp free grating of 30mm length should give a narrowband reflectivity of less than 0.1nm width. This discrepancy is due to the holographic grating definition with spherical wavefronts of small curvature inducing a weak chirp of the grating periodicity. This chirp reduces the peak reflectivity and broadens the overall response, but cannot completely explain the unusual wavelength dependence, which might be caused by inhomogeneities of the grating depth and/or the waveguide effective index.

Laser operation: A colour centre laser with an output power of up to 220mW at $\lambda_p = 1484nm$ was used as the pump source. The polarisation of the pump was chosen as σ (TE) because maximum gain is achieved with both pump and signal σ polarised. The pump light was launched via a singlemode fibre by butt-coupling to the laser resonator. In this way a Fabry-Perot cavity is formed by the end face of the fibre and one of the resonator mirrors, leading to an effective pump (and/or signal) reflectivity which depends on the fibre-chip distance. This results in an uncertainty in the absolute values of coupled pump power. The values given below can be taken as upper limits because they were not corrected to take the effective endface/mirror reflectivities into account. All results presented in the following are from the same optical waveguide and grating. DBR laser operation with the three different resonator configurations presented above has been investigated:

In configuration (i) the pump radiation is coupled into the cavity from the left (Fig. 1); the laser output is monitored in the backward direction. A threshold of 135mW coupled pump power is observed. With 180mW the CW-laser output reaches 1.8mW, corresponding to a slope efficiency of 3.8% (Fig. 3).

In configuration (ii) the pump is coupled into the cavity through the DBR grating (from the right), resulting in a double pass pumping scheme. Again, the laser emission is monitored in the backward direction. Unfortunately, the advantage of double pass pumping is more than negated by the high excess loss for the pump if fed through the Bragg grating. Coupling to substrate modes leads to a loss of 3dB/cm. This causes a threshold power of 180mW.

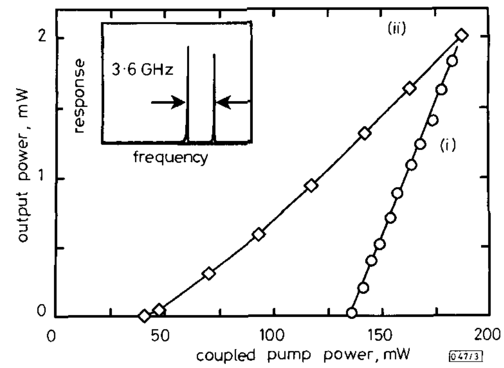

Fig. 3 *Output power against coupled pump power*

Inset: emission spectrum
(i) η ≃ 3.8%
(ii) η ≃ 1.5%

In configuration (iii) the laser is pumped from the left through the dichroic, dielectric mirror; the laser output is monitored through the grating. A great reduction in laser threshold down to 40mW was achieved; the slope efficiency is 1.5%. However, owing to the lower threshold, up to 2.0mW of output power could be generated with a coupled pump power of 185mW (Fig. 3). The bandwidth of the laser emission was measured with a bulk scanning Fabry-Perot spectrum analyser of 15GHz free spectral range. The DBR lasers oscillate with a few (1-4) longitudinal modes (mode spacing: 1.8GHz). Frequently, every second mode is suppressed, leading to a typical output spectrum as presented in the inset of Fig. 3.

Conclusions: We demonstrated the first integrated optical DBR laser in $Er:LiNbO_3$. The best of three different resonator configurations has a threshold of only 40mW coupled pump power and yields a maximum output power of 2mW. The laser emission has a small bandwidth; sometimes even single-frequency operation is observed. The DBR laser can be monolithically integrated with further components on the same $LiNbO_3$ chip. This will allow us to develop optical circuits of larger complexity and higher functionality than possible today.

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