Publishable final activity report

Project execution

- ### Introduction

Diode lasers are more efficient than any other laser and feature the highest reliability. They are already very strong contenders in the commercial marketplace. Laser diodes are a basic technology for a diversity of applications, such as pumping of solid-state lasers, communications and material processing. At the same time, there are clearly certain deficiencies in their performance that have become critical for many demanding applications e.g. their low spatial and temporal coherence. The consequences of this are a too broad spectral line-width and a poor beam quality.

With respect to the spectral range, present laser diode technology (especially for high power) is limited to the near infrared region. Recent advances of GaN technology has resulted in the commercialisation of low power (several tens of mW) blue laser diodes around 400 nm. However, large portions of the spectrum are not yet covered by laser diodes.

The main aim of this project is the development of low cost, mass production technology for optical components based on volume Bragg gratings (VBG) in advanced photorefractive materials that control the spatial and temporal coherence of laser diode radiation. As a result, a new generation of diode lasers with a very narrow line width and high spatial coherence will be developed and commercialised. As a logical continuation, the second aim is the integration of nonlinear crystals with periodic domain inversion. These will enable the efficient frequency conversion of the high brightness, narrow band laser diode radiation by means of second harmonic generation.

This new generation of lasers will find many new applications in different markets. The frequency converted lasers will cover large portions of the spectrum that are not attainable at present by laser diodes.

- ### Project objectives

1. *Development and prototyping of volume Bragg gratings and Bragg structures in photorefractive glass (PRG) and photorefractive polymer (PRP)*

a) Volume Bragg gratings will be designed and fabricated in a photorefractive glass samples optically polished and antireflection coated at the laser wavelength. Reflection efficiency is aimed at 40 % to 80 % and it will be measured and controlled.

b) Dispersive components are generated in photorefractive polymer samples. This includes the fabrication of Bragg-gratings (surface relief gratings / volume gratings) and integrated-optical Bragg-structures into the component substrate surface. The Bragg-reflection efficiency is expected to be between 40 % and 60 %, the Bragg-reflection bandwidth is less than 2 nm. The dispersive components can be operated in the near IR-area and have an operation temperature up to 85 °C.

2. *Laser diode spectral narrowing and stabilization*

a) Single emitter laser diodes and laser diode arrays (bars) will be fast and slow axes collimated and by forming an additional optical cavity using the volume Bragg grating (VBG) structures the laser spectrum will be narrowed.
Laser bars with very high output power will be combined with Bragg gratings to produce output power in the range 10 W to 40 W with very narrow spectrum and high temperature stability.

b) The polymeric dispersive components, which are located outside of the laser diodes cavities, will externally stabilize the single emitter laser diodes by narrowing the wavelength spectrum of the emitted laser beam. The polymeric dispersive components will be only used for low-power-laser diode applications.

3. Periodically poled nonlinear crystals (PP-NLC) for efficient frequency light conversion

Samples of PP-NLC will de designed, fabricated and tested. Conversion efficiency to second harmonic of > 60 % is set as a goal.

4. Frequency-doubled laser diodes with volume Bragg gratings and nonlinear crystals

a) The combination of spectral narrowed laser diode and efficient frequency converters will be used to create a novel coherent light source of visible laser radiation.

b) Aimed parameter for single emitter laser diodes is an output power in the range 0.05 W to 0.3 W in the visible range (400 nm – 550 nm wavelength).

c) For laser bars, an output power in the range 1.0 W to 3 W in the visible range (400 nm – 550 nm wavelength) is set as a goal.

• Contractors involved

SICO Technology GmbH, Bleiberg-Nötsch 176, A-9530 Bad Bleiberg, Austria (SME)

Daren Laboratories and Scientific Consultands Ltd., Hamazmerah 13, 74047 Ness Ziona, Israel (SME)

ALPHALAS GmbH, Bertha-von-Suttner-Str. 5, D-37085 Göttingen, Germany (SME)

BIAS - Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Straße 2, D-28359 Bremen
Germany (RTD)

UFE – Institute of Photonics and Electronics, v.v.i.
Academy of Sciences of the Czech Republic, Chaberska 57, CZ-18251 Prague 8, Czech Republic (RTD)

Foundation for Research and Technology - Hellas (FO.R.T.H.), Vassilika Vouton, PO Box 1527
71110 Heraklion, Crete, Greece (RTD)

Universitat de Valencia – Estudi General, Avenida Blasco Ibanez 13, 46010 Valencia, Spain (RTD)

• Co-ordinator contact details

BIAS - Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Straße 2, D-28359 Bremen
Germany, Coordinator: Prof. Dr.-Ing. Frank Vollertsen, Contact person: Dipl.-Phys. Michael Koerdt
(Phone.: +49/421/218-5044, Fax: +49/421/218-5063, e-mail: koerdt@bias.de)

• Work performed

Within the first project period one of the main targets was to generate first volume Bragg gratings in photorefractive glass and polymer materials. Therefore materials with the required photorefractive characteristics have been fabricated. Further a phase mask method facility was developed for volume Bragg grating fabrication. The second target is the development of a technology for the realization of a periodic modulation of the properties of nonlinear optical crystals. Therefore reviews of the periodically-poled nonlinear crystals and of the state of the art in these materials were done. After that a full technological cycle for electrical poling of nonlinear optical crystals has been developed and tested.

The development and synthesis of the photorefractive materials were done by the SME performers that were supported by the participating RTD's in terms of materials selection. The development of the fabrication technologies and the characterization experiments of the optical components were done by the RTD-performers. Furthermore theoretical work was done by the RTD-performers. In this work a volume Bragg grating simulation software was developed.

Within the second project period one of the main targets was to generate optimized volume Bragg gratings in photorefractive glass and polymer materials. Therefore the knowledge about the photorefractive materials generated in the first project period was used to fabricate glass and polymer materials with the required photorefractive characteristics. Further a two beam interference (Lloyd mirror) method facility was developed for volume Bragg grating fabrication. The improvement of the fabrication technologies and the characterization experiments of these optical components were done by the RTD-performers.

The second target was the optimization of the properties of nonlinear optical crystals. Therefore the technology for the realization of the periodically-poled nonlinear crystals was improved. With the developed optical components a laser diode system was developed and characterised.

- **End results**

Calculations with the developed Bragg grating simulation software shown that only weak variations of the refractive index of around 0.00005 are needed over a length of several millimetres for non saturated reflectivity and sharp reflectivity spectrum. After an extensive review of the literature on material systems and discussions between all the partners the priorities of the nonlinear materials were narrowed down to the crystal RTP. This material was chosen because it had high efficiency, could be manufactured in the time scale of the project, and had a period of domain inversion that was realistic. Also a review was carried out of the calculation methods of determining: poling period, spectral bandwidth, temperature bandwidth, and angular bandwidth given the pump wavelength, crystal length, ambient temperature, crystal axis, and the refractive index dispersion relation. The dispersion relation of the various crystals was taken from the current literature as well.

Within the project photo-thermo-refractive glasses with proved photorefractive characteristic have been fabricated (see Fig.1). The results of the work with the synthesis of photorefractive polymer material are the following: The components of the monomer mixture were established. A convenient for polymerization mold was designed and manufactured. Highly (>92 %) transparent plates with high T_g (>140 °C) have been obtained (see Fig. 2).

With these polymers the fabrication of volume Bragg gratings with the developed phase mask method facility reached the state that volume Bragg gratings with the required Bragg refraction efficiency can be realized. The Bragg refraction of such a volume Bragg grating is shown by Fig. 3. Planar waveguide Bragg components were fabricated also. An example of such a component is shown by Fig. 4.

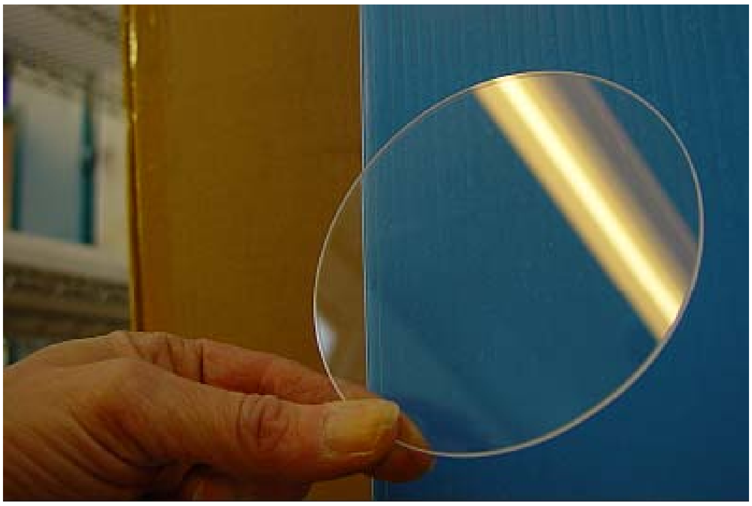

Fig. 1: Polished photosensitive glass disc

Fig. 2: Photosensitive polymer disc

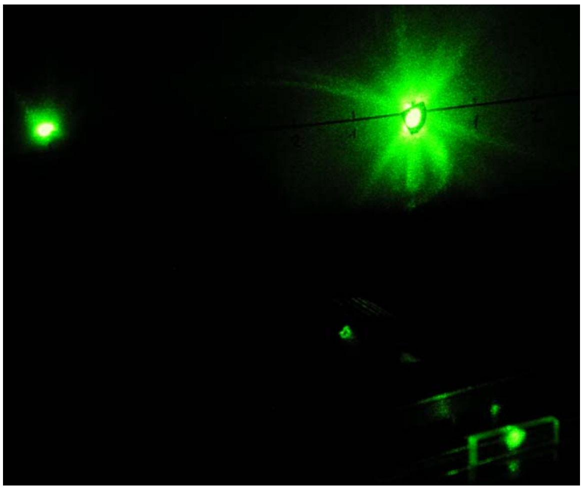

Fig. 3: Bragg refraction of a volume grating

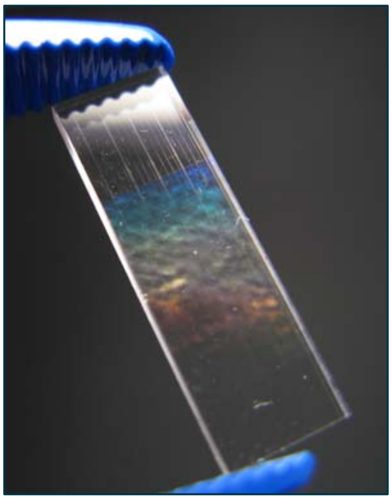

Fig. 4: Inscribed waveguide Bragg structures

The polymer material for waveguide fabrication has a low depth of penetration for ultra violet radiation and a high refractive index change. So this material can serve as substrate and waveguide as well and therefore it has with respect to other material systems advantages because only one bulk polymer is required for production of waveguide structures.

The results of the work with the nonlinear crystals are the following: A full technological cycle for electrical poling of nonlinear optical crystals: RTP and its isomorphs have been developed. Z-cut plates with polished z-planes are the input in the cycle and periodically poled structures are the output of the technological cycle. The cycle includes also all essential characterization techniques. Besides the fabrication of photolithographic masks all other steps were realized. The cycle was successfully tested on example of electrically reversely poled RTP structures designed for quasi-phase matched second harmonic generation of 1064 nm. Fig. 5 shows a demonstration of second harmonic generation (SHG) from 976 nm wavelength.

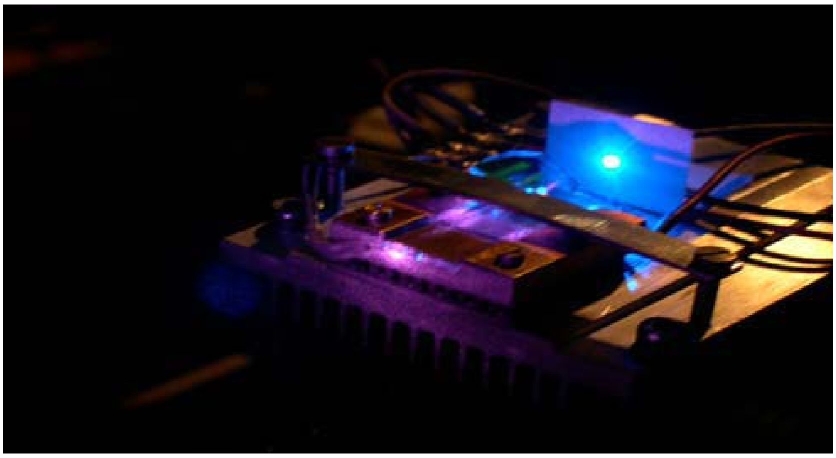

Fig. 5: Frequency doubling of 976 nm-radiation with a NL-PPC manufactured at IPE

The setup at ALPHALAS for demonstrating the efficient bandwidth-narrowing, frequency-stabilization and frequency-doubling of laser diodes was successfully built up, all components produced by IPE and BIAS meet the requirements. The bandwidth of the frequency-narrowed laser diode was below 0.1 nm, the single-pass frequency-doubling efficiency of 976 nm to 488 nm was about 1/600, which is an excellent result for this wavelength. The result is very promising for creating a pulsed laser source at 488 nm for replacing low-power Ar-Ion lasers.

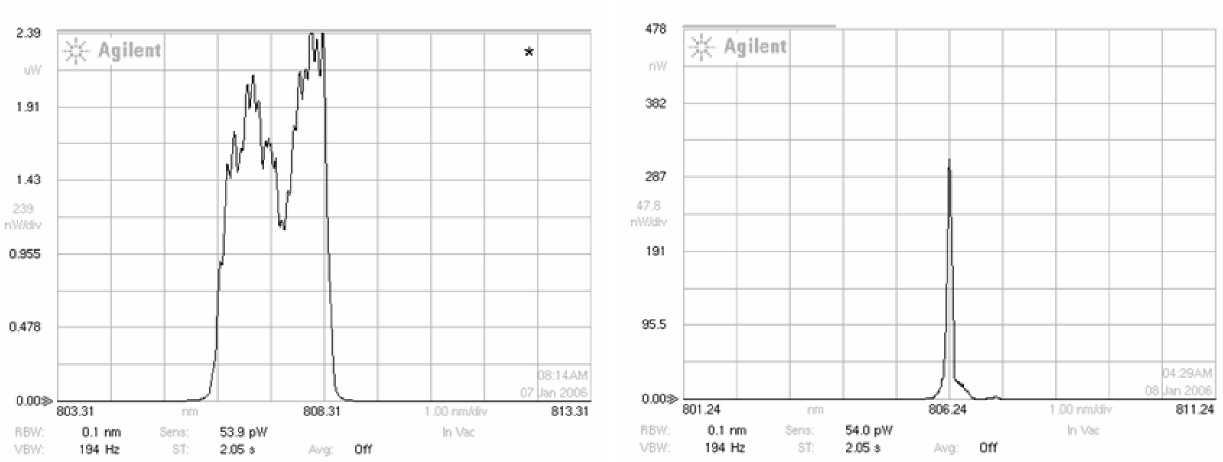

Fig. 6: Spectra of laser diodes without stabilization (left) and with stabilization using a VBG (right)

The end result of the project is a new range of frequency converted laser systems with very narrow line width and high spatial coherence. Therefore volume Bragg gratings with the required efficiency and periodically-poled nonlinear crystals fabricated in the project are existent.

The project was executed successfully. The main goals were achieved. The demonstrators reported on are an excellent starting point for the successful product commercialization. As the demonstration of freqnency stabilisation and frequency doubling have been very successful, SICO and ALPHALAS both plan to continue the production of VBGs for frequency stabilisation on their own costs in order to enhance the beam properties of laser diodes.

• Impact of the project on its industry

In the framework of the project, each partner develops a special advanced product which will not only decisively contribute to the achievement of the project objective, but can also be marketed separately for many advanced applications. This will promote each SME partner to a better marketing and competitive position worldwide.

Photorefractive materials produced by SICO Technology GmbH and Daren Laboratories and Scientific Consultands Ltd. find an advanced photonic application in the optical information technology, telecommunication and military industry. ALPHALAS GmbH will produce diode laser systems with improved spatial and spectral characteristics as well as periodically poled nonlinear crystals and highly efficient frequency doubled laser diodes based on the materials and technologies developed in the project. Also ALPHALAS and SICO both will continue the manufacturing of volume Bragg gratings to stabilize laser diodes with these components.

In the above mentioned sectors a lot of European SMEs are working. Many of these European SMEs can potentially benefit from the new developments. For example, all sectors which deal with suitable optical devices, systems and technologies can profit from the results of this project.

The cooperation in the BrightLight project leads to a transfer of information and knowledge and the reinforcement of Europe in the field of optical technology and fabrication of trendsetting laser systems in the face of worldwide competition.

• Reference to the project public website

The internet address of the public website is the following:
http://www.bias.de/Abteilungen/SOT/Projekte/BrightLight/