DEVELOPMENT OF ORIGINAL OPTICAL AND QUANTUM ELECTRONICS DEVICES FOR APPLICATIONS IN COMMUNICATIONS, METROLOGY AND SCIENCES

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Abstract: The goal of the report is to present the development – principles, theories and computer simulations, experiments and practical realizations, of original and competitive methods, elements and devices for quantum electronics, optical communications, metrology, remote sensing and sciences: multi-channel WDM system with independent tuning of each input/output, multi-wavelength laser with independent control of each wavelength, lasers with emission, spectrally fixed at reference atomic absorption line, injection-locking laser system for high (~10^6-10^8) and linear amplification of low-power (~ µW, nW) modulated laser light, optical analogue of the transistor action – optical transistor, system for remote (up to kilometres) measurement of small (mm) translational elongation – shrinking of objects, new solution of tunable sub-nanosecond lasers and lasers with rectangular nanosecond (~1 ns) pulse emission, including controlled duration and tunable wavelength. The basic element of the devices developed is stable and compact interference wedged structures in new composite solution with very narrow transmission (≤ 0.01 nm) in relatively large spectral range (≥1 nm). The laser active media used are solid-state, semiconductor and dye.

1 INTRODUCTION

The report is a review of our recent results, concerning the further development of original quantum electronics and optical devices with a potential for competitive applications in optical communications, metrology, scientific work, and atmospheric pollution monitoring. The aim of the report is to present as a whole complex our last achievements in the development – experiments, theories, and practical realizations of an original WDM system with independent tuning of each input and output, system for remote (to kilometres) measurement of small (mm) translational elongation - shrinking of objects, optical transistor, multi-wavelength lasers with independent control of each wavelength and with wavelength emission in single beam or in closely parallel or coaxial beams, the new solution of tunable sub-nanosecond lasers, the lasers with emission, spectrally fixed at reference atomic absorption line. The basic elements, used and studied by us are a wedged interference structure (variation of the Fizeau Wedge), including some researched of found by us new properties. The essential part of the results is obtained in our group at the Technical University of Sofia, Branch Plovdiv and the University CNAM-Paris, the University of North Paris and the University "Sent Quentin" – Versailles, France. The principal authors' publications from the last years, where the discussed here results are given in details, are the firs 13 articles, given in the References at the end of the paper. The authors of the report, that are the main co-authors of the noted works, have selected and systematized the materials; also the essential part is based on their propositions – primarily given in their patents and previous articles followed the noted firs ones, except the last well known laser book [Svelto,1998]. The report includes also completely new, non-published results. The articles of the other authors, related with the subject of the presentation, are given as citation in the noted

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authors' publications. Following the actual authors' professional activity, the report concerns mainly the technical aspects of the problems. Nevertheless, the necessary physical moments to clarify the principle of the developed methods and devices are also given shortly.

The general objective of the work is to establish these new and effective devices in science and practice as novel components of the main hardware basis in the indicated areas. In parallell, new knowledge in the field of quantum electronics and optical interferometry is obtained. The envisaged solutions have encountered their preliminary positive approbation firstly in the working laboratory models as well as in the cited below recent publications in the specialized journals.

2 NEW ELEMENTS AND DEVICES IN ACTUAL DEVELOPMENT

2.1 Original optical elements based on wedged interference structures and their applications

Furstly, we will present the further development and examine thoroughly the original optical elements and system for noted in the introduction applications. Proposed devices are based on the use of the wedged interference structure of Fizeau type Interferometer - Interference Wedge (IW). The development include ideas, experiments, theory and proposed applications developed by us. It is applicable in the case of limited diameter beam illumination [Nenchev, 1982; Stoykova, 2010; Nenchev, 1993; Stoykova, 1993; Deneva, 2007; Deneva, 1996]. The new proposition, except our previosly introduced new optical element based on a Reflecting Interference Wedge [Nenchev, 1982], includes a new WDM (wavelength division multiplexing) element with an important property allowing spectral tuning of inputs/outputs in the simplest manner. The importance of WDM structures for the optical communications is undisputable and is described in the most popular textbooks. Also, we describe the new system with IW for remote (meters, kilometers) measurement of the translational expansion and shrinking of objects.

The principle of our proposed WDM structure can be clarified with the Figures given below. The interference wedge (IW) of thickness of the order of micrometers plays the role of a spectrally selective filter and a channel coupler, being a near totally reflecting mirror for the non-resonant wavelengths. The new, generalizing theoretical and experimental physical treatment of the IW is described in our cited papers [Stoykova 2010; Nenchev 1993; Stoykova 1996].

The Fizeau interferometer or interferential wedge (IW) consists of two reflecting plane surfaces separated by a gap with linearly increasing thickness. A low-reflectivity coated wedge has been used before us as un effective tool in surface topography, as a high-resolution broadband wave-meter. Multiple-beam interference in IW has been addressed for implementation of phase-shifting Fizeau interference microscopy. As a rule, theoretical and experimental analysis of the IW properties by the other authors were conducted mainly for the case of infinite plane-wave illumination assuming an extended wedged structure; different wedge applications have been also analyzed for this particular case. Inspired by IW incorporation in laser design, over the recent years we focused our efforts on the study of compact wedged interference structures under illumination with a narrow light beam of small diameter. We have succeeded to reveal unique properties of the IW when illuminated with laser light, and to propose various applications, thus insuring the IW as a competitive optical element in laser resonator design [Deneva, 2007; Louyer, 2003; Stoykova, 1996; Goris-Neveux, 1995]. A high-reflectivity coating IW with thickness of tens of millimetres has spectral resolution comparable to that of the Fabry-Perot interferometer, but at additional advantage of linear spectral tuning by means of translation in its plane. Such IW, with apex angle of 5–100 μrad and thickness of 5–500 μm has been used by us in laser resonators technique to create two-channel resonators with independently controlled characteristics of the produced two-wavelength emission, as a spectrally selective reflecting or transmitting optical element of resonant wavelength easily adjustable by translation of the interferometer. Selective wedge transmission and reflection has been used for continuous tuning of the selected mode in high-purity single mode lasers, unidirectional lasing in ring resonators, two-wavelength laser operation, narrow line selection and tuning of wide-gain lasers.

A simple and effective solution of a multi-wavelength spectrally selective resonant structure for two-wavelength lasers with independent tuning at each wavelength has been proposed by the authors [Nenchev, 1981; Deneva, 2007; Louyer, 2003, Gorris-Neveux, 1995]. It makes the use of valuable optical features of the IWs. In particular, we advanced a reflecting IW as a completely new laser spectral selector. The proposed structure has been patented and successfully applied in multi-wavelength laser technology for dye, Ti:Sapphire Yb:YAG, and semiconductor lasers.

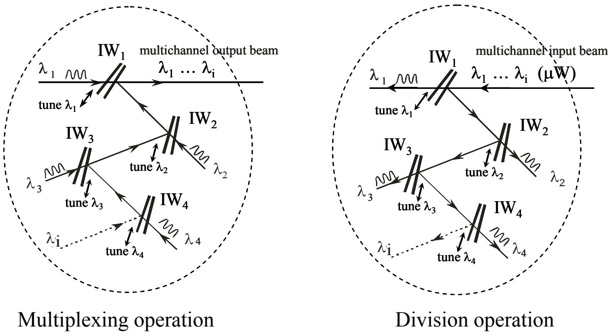


Figure 1. Schematic presentation of new WDM structure.

Generally speaking, it could be considered as a new and competitive solution of a WDM element for optical communications.

The high-reflectivity coatings IW of thickness of 5-300 μm acts simultaneously as a spectrally selective filter and a channel coupler, being a nearly totally reflecting mirror for the off-resonant wavelengths. In addition, tuning of the transmission maxima is provided by simple translation of the IW in its plane. Figure 1 represents schematically the operation of the proposed new WDM structure for the cases of multi-wavelength input or output beam. The tuning of each output by translation of the corresponding IW in its plane does not affect the geometry of the structure and the characteristics of the other outputs respectively. Also, as it is clear from the figure, the structure gives the possibility to obtain superposition of individual beams which have passed through each IW, thus serving as a multi-beam multiplexing element for the spectrally different beams (each of them being a resonant beam for the corresponding IW and off-resonant beam for the other IWs).

Analysis of the WDM element requires first to analyze the behaviour of a separate IW for laser (coherent) beam illumination.

We adopted the mathematical model for computer simulation and developed an adequate description of transmittance and reflection of the IW for a limited diameter laser (coherent) beam (~1-1.5 mm). [Nenchev, 1993; Stoykova, 2010] Thus, our treatment differs essentially from the plane-wave illumination approach.

The detailed calculations are given in our works [Stoikova, 2010; Nenchev, 1993; Stoykova, 2001].

The calculations were made for two types of interference wedges. The first one is a “sandwich type” IW, formed by sequential layer-by-layer deposition of a dielectric reflective coating of reflectivity 0.9 on both sides of the glass plate, which represents a wedged transparent layer with optical thickness of 5 μm. The other type of the IW is the silica wedge with optical thickness of 300 μm having dielectric layers on both surfaces of equal reflectivity of 0.9 in a spectral region of ~ 30 nm around the wavelength of 630 nm. The apex angle of both wedges is α = 0.05 mrad. The described IWs, which are of essential interest as high-resolution spectral selective elements, are simple for production and use. The “sandwich type” IW is very convenient for application in the new WDM structure due to its compactness.

A typical curve, calculated for illumination with a CW laser Gaussian beam in the region of its flat front (flat-concave resonator, near the flat output mirror), is shown in Figure 2. We see that the IW is a highly transmissive narrow-line filter for the resonant wavelength and approximately totally reflecting mirror for the off-resonant wavelength.

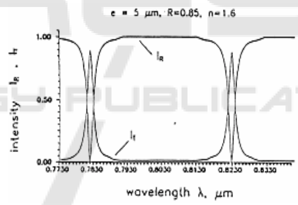


Figure 2. Calculated transmission and reflection curves as a function of the wavelength for a “sandwich”-type IW (CW laser beam illumination).

As a second step, we have studied wedge behavior for illumination with short laser pulses, including the sub-nanosecond light pulses. The calculations are made at different wavelengths near ~ 0.6 μm. The obtained results are similar to those in the case of CW beam illumination.

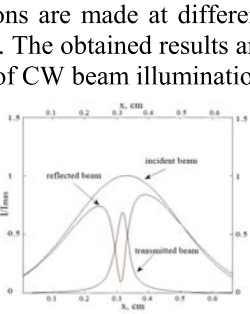


Figure 3. Transmission and reflection for pulse illumination (0.5 ns pulse duration); e=5 μm.

Figure 3 gives the typical computed curves for the "sandwich type" IW irradiated with pulses of duration of 0.5 ns (the axis *x* in Figure 3 gives the distance along the beam impact area from an arbitrary chosen zero-point) [Nenchev, 2011].

As it can be seen from the depicted curves, the transmission and reflection properties of the wedge do not change essentially. Transmission reaches about 60 % for the pulse duration of ~ 0.1 ns that may correspond to frequency repetition rate of ~ 10 GHz. Therefore, the presented calculation shows feasibility of the proposed WDM structure.

We realized experimentally our WDM structure for the case of CW beam illumination using a laboratory model of free-communication system. We formed a single laser beam by exact superposition of the emissions of three CW lasers – two He-Ne lasers emitting at 0.63 μm and at 0.59 μm respectively and the frequency doubled Nd:YAG laser (0.53 μm). The beam diameter was ~ 1 mm. Figure 4(a) presents the WDM structure, composed of 3 "sandwich type" wedges with thickness *e* = 5 μm, each of them tuned to one of the wavelengths in the green, yellow and red spectral regions, respectively.

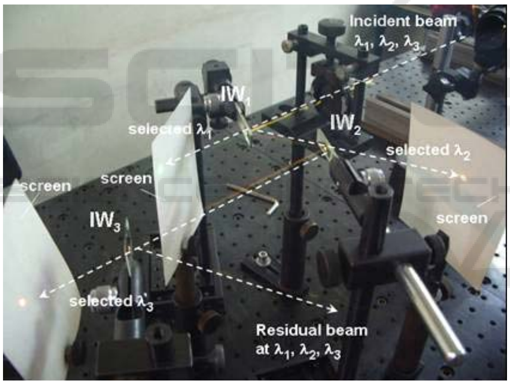


Figure 4(a). The experimental set-up presents the realized WDM device, composed of 3 wedges, each of them to a separate channel – green, yellow and red, respectively.

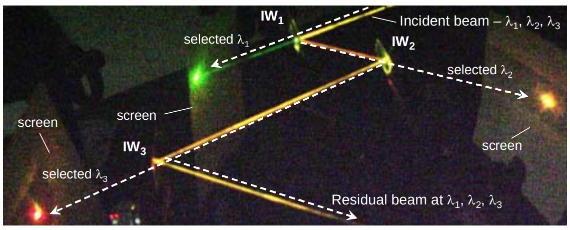


Figure 4(b). Visualization of the channel-separation (colors) by the new WDM-arrangement in the laboratory model

As it is shown in Figure 4(b) by using smoke visualization and screens, wavelengths separation has been achieved. By translation of the wedges, we can independently tune the resonance and the given output. The laboratory WDM is shown in Figure 5.

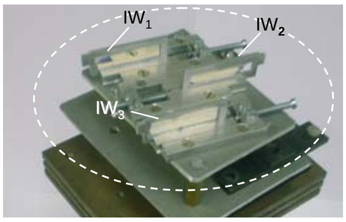


Figure 5. Realization of the compact working experimental model of the proposed WDM structure

The calculation shows the same type of dependences for the silica gap IW with optical thickness of 300 μm (Figure 6(a)) .

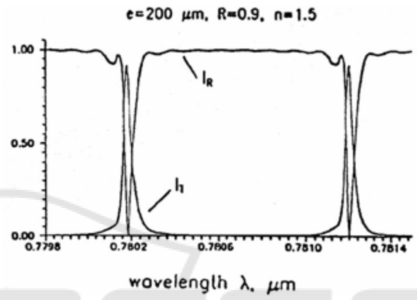


Figure 6(a). Calculated curves as in Figure 3, but for thick silica-gap 200 μm IW.

The essential advantage of this silica gap thick IW is the higher spectral resolution in comparison with the "sandwich type" structure whose thickness is technologically limited to few μm, and respectively does not permit to obtain a transmission line low than few part of nanometers. However, there is the problem related of obtaining a selection by the standard IW structure of a narrow line in combination with high separation between the resonant lines (Figure 6(a)). The calculations show that there are completely similar dependence between the width of the selected line $\delta\lambda$ and the spectral distance $\Delta\lambda$ between the lines as this one for FPI - e.g. $\delta\lambda = \Delta\lambda/F$, where F is the fines factor, depending on R. Thus the desired low value of $\delta\lambda$ leads to low value of $\Delta\lambda$ .This limits the selectivity of the channels in optical communication system.

The principle of our solution of this problem is based on the use of composite wedged interference structure. It can be understood from Figure 6(b) where is given schematically one example of composed two-component structure.

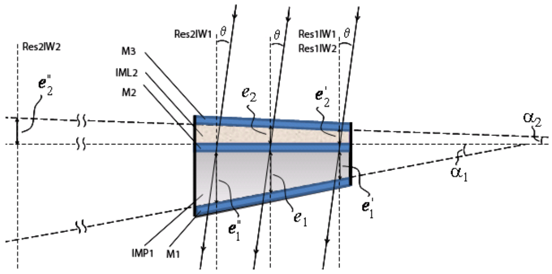


Figure 6(b). Schematic of the new composite wedged interference structure.

It consists of one thick wedge e.g. e_1=200 µm optical thickness silica glass wedge with two dielectric mirrors at each wedge plane with reflectivity of R=0.95%. The wedge angle α_1 of the plate in the example is α_1= 200 µrad. On the one of the mirrors is lay a transparent wedged layer with thickness e_2=10 µm and wedge angle α_2. The relatively simple calculations give that if the angle α_1 and thickness e_1, and the angle α_2 and the thickness e_2 are chosen to be in the relation

$$\alpha_2 = \alpha_1 . e_2 / e_1$$

the change of the resonant maximums of both connected wedges with the translation of the composite system in its plane is exactly equal. In this system the thick wedge gives a very low spectral width of the transmission of all system (~0.05 nm) and the thin wedge selects only single resonance of the thick wedge at high spectral range (~ 15 nm and higher). Typical example of computer calculated resonances at the described system is given in Figure 6(c).

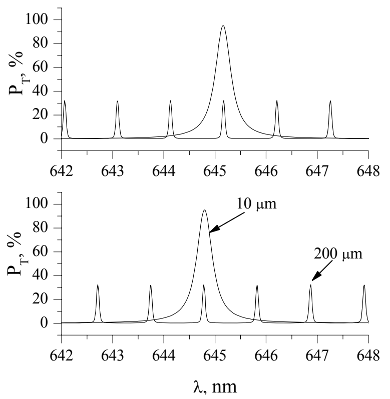


Figure 6(c). Computed transmission of the composite wedged structure, formed by two IW (10 µm and 200 µm) with convenient wedge angles and the tuning (see the text)

As a second task, we have proposed new and attractive utilization of the IW specific properties by designing devices, which allow distant (from few meters to millimeters) laser measurement of small (~mm) linear translation of a rigid object.

The principle of our device can be understood from Figure 7, which shows as an example - measurement of small linear stretching of a steel hammer-beam due to change of the IW transmission resonance in the beam incident point.

The set-up contains a comparative system of one beam-splitter and two photo-receivers. One of them records that part of the emitted beam, which forms reference intensity and the other one records the light transmitted by the IW. Due to translation of the IW, the transmitted light decreases. By tuning the laser, we can obtain new resonant wavelength, λ_2, corresponding to the new wedge thickness. Indication for this is the new peak in the transmitted light that is recorded by the corresponding receiver. From λ_1 and λ_2 it is easy to calculate the translation distance Δx, of the invar plate. Figure 8 proves the high sensitivity of the proposed method. For high precision measurements of translations in sub-millimeter region, a single-mode semiconductor, Titanium Sapphire or dye lasers can be used.

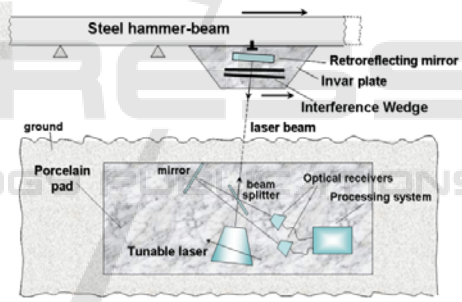


Figure 7. Device based on IW for distant measurement of small translation of a rigid object in its plane.

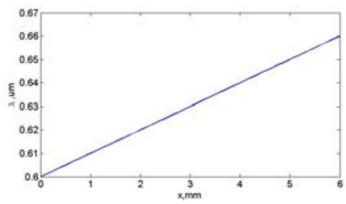


Figure 8. Calculated dependence of the resonance wavelength at different points along the IW.

For the case of remote (meters, kilometers) measurement of the translational stretching - contraction of objects the second type of system, which is other variant of the idea, discussed above, is developed. This system eliminates the increasing of the diameter of the laser beam due to the natural divergence, also the fluctuation of the illuminated intensity and the need of exact beam direction on the Interference Wedge (which is a small dimension element). The action of the system is clarified from given Figure 9. Here, we introduce an Ulbricht sphere and lens, as it is shown in Figure 9, to eliminate the noted above problems for remote measurement at long distance. The radio-transmitter system or reflection of modulated by information about translation part of the incident light transmit the two signals in the processing system. Thus, we obtain the correct relative value of the transmitted signal, what eliminate the influences of the beam intensity fluctuations and the incident place of laser-beam cross-section, illuminating the lens.

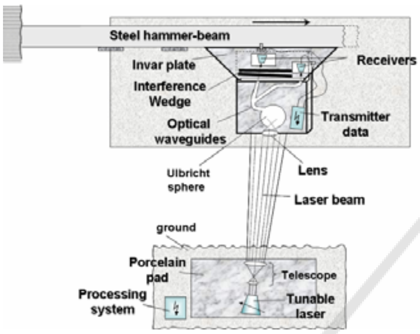


Figure 9. Device for remote (kilometers) measurement of small translations of a rigid object in its plane that uses IW and Ulbricht sphere.

The developed laser-Interference wedge devices can be of interest to control the metal or concrete hammer-beam length variation (with the temperature or earthquake) of bridges, of platforms for oil extraction in the sea, of walls of the buildings etc.

2.2. Original multi-wavelength lasers with independent control of each wavelength using the WDM structures developed in 2.1.

An important goal is the achievement of two- and multi-wavelength generation of nano- and sub-nanosecond pulses with implementation of our group's original methodology as well as development of multi wavelength generators of the same type based on semiconductor active media [Nenchev, 1995].

Our group has substantial expertise in the development of two-wavelength lasers [Deneva, 2010; Louyer, 2003; Slavov, 1998, Gorris-Neveux, 1995; Nenchev, 1981]. Using our original approach we were the first in the world to develop with the corresponding theoretical and experimental background two-wavelength F-centers, Ti-Sapphire (in pulsed mode) and Yb:YAG lasers, (in a CW diode pumped mode) – [Loyer, 2003; Goris Neveux, 1995]). The laser solutions are based on our proposed effective multichannel resonator with a complex selector-coupler structure based of IWs [Nenchev, 1981]. Using the described above multi-channel WDM element new and simple solution of multi-wavelength lasers are proposed with independent tuning of each wavelength. Two types of solution are given in Figure 10(a) and 10(b). The scheme in Figure 10(a) is solution in which the emission of the two wavelengths is in single laser output beam. For many cases where single volume needs to be illuminated exactly (e.g. in remote atmosphere pollution control) and high speed processes (e.g. explosion) this solution is advantageous. The difficulty for multi-wavelength operation is related to strong wavelength competition effects in homogeneously broadened active medium – e.g. dye, semiconductors. It follows that it is necessary to make a very precise balance for net gain for all wavelengths at each tuning or strongly limit the tuning range around the gain maximum – in its flat part. The second scheme with closely spaced parallel beams at each wavelength – in Figure 10(b) - eliminates the problem of competition, however the laser light at the separated wavelengths acts upon different parts of the illuminated volume (superposition can be obtained after focusing in small length of ~ mm).

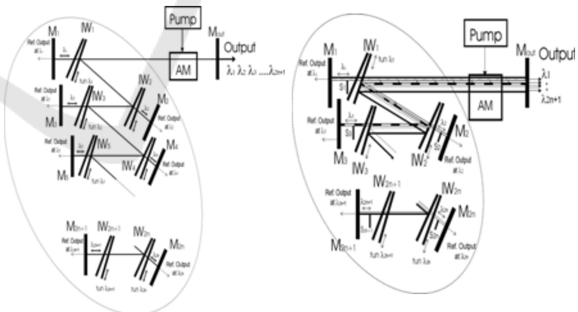


Figure10. WDM multi-wavelength laser resonator schemes with independent tuning at each wavelength; (a) –with output in single beam, (b) – with closely parallel outputs.

Except the previously realized, used and described in the specialized literature dye, Ti-Sapphire, F-colour centres and Yb:YAG lasers, in our recent works we have practically developed a two-wavelength semiconductor laser. The laser emits at two independently tunable wavelengths in a single beam. To obtain a small diameter of the incident beam at the selected IWs, we modified the scheme in Figure 10(a) using the focussing and the flat end mirrors as it is shown in the Figure 11. We have realised (Figure 12) such two-wavelength semiconductor laser using a red laser diode with antireflection coated output surface. The laser

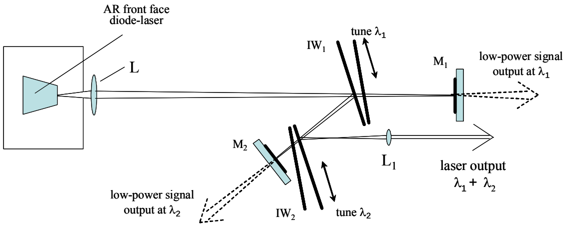


Figure 11. Schematic diagram of the modified resonator, given in Figure 10(a) and adapted for two-wavelength generation with independent tuning of each wavelength in large beam semiconductor active media.

operates successfully at two wavelengths. As a rule the lasing starts firstly in one of the channels. To obtain also lasing in the other channel we slowly increased the losses for the started generation, in practice by misalignment of the end mirror in its channel. This can be obtained if the wavelength is spectrally near the maximum of the gain. At each tuning of one wavelength it was necessary to arrange again the losses at the generated channel to obtain the lasing also at the second wavelength. In this manner tuning range of ~ 4 nm for each wavelength in two-wavelength operation can be achieved. By oscilloscope studies we found that both wavelengths are generated simultaneously. This laser can be useful in some experimental works needed in two-wavelength operation. Our next work is related to realization of the second, wavelength competition less, scheme given in Figure 10(b). The new solution is combined with passive self-injection [Keller, 2000] what abruptly increases the laser efficiency.

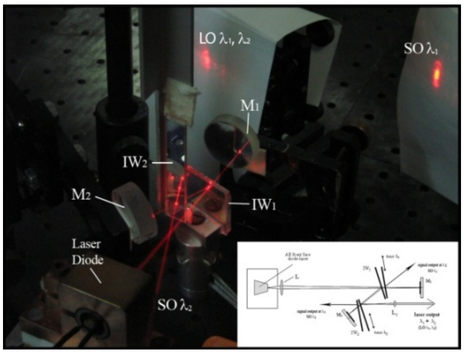


Figure 12. Photograph of the operating two-wavelength semiconductor red laser. The generation is at two wavelengths λ_1 and λ_2 in separated reference outputs and in main, common output.

2.3 Actual our development of a high-power two-wavelength wavelengths competition-less Nd:YAG laser

Earlier [Nenchev, 1978], we have patented a flashlamp pumped laser where single active element operates in two parts separately and at two different wavelength. Actually, we have developed this technique using single, flash-lamp pumped (~150 J pump) Nd:YAG crystal to obtain simultaneous or in controlled manner generation at two chosen lasing

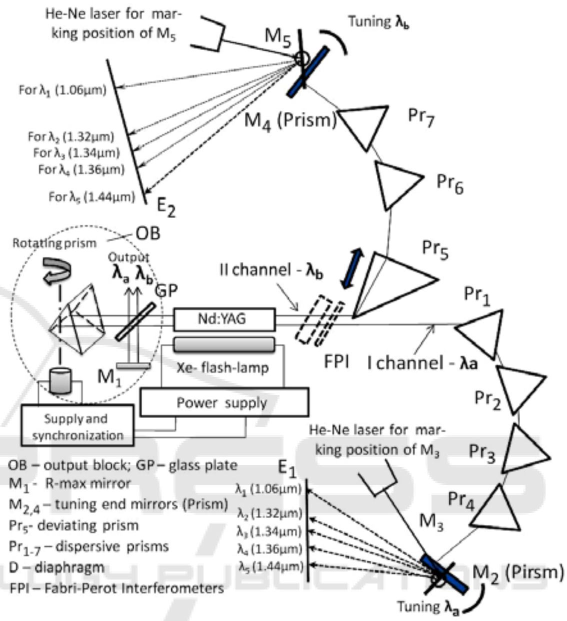


Figure 13(a). Schematic of the two-wavelength, flashlamp pumped, Q-switched, laser that uses two separate parts of a single Nd:YAG crystal and prisms selective structure.

lines - pair-combination from the possible generating lines: 1.06 µm (to 0.8 J), 1.32 µm, 1.34 µm, 1.36 µm (to ~ 0.14 J) and 1.44 µm (to ~0.03 mJ, none well reproducible) and avoiding the limiting wavelength-competition effect. The laser (Figure 13(a)) can also operate at two chosen modes at different frequency distance from the standard for single cavity lasers (c/2L). We use the generations in two separate parts of the single, flashlamp pumped Nd:YAG crystal in two manner: i) in coaxial separation and ii) in two closely spaced parts by prism selected-tuning resonators (for the single-mode case with introduced glass-plate Fabry-Perot interferometers).

The design of this laser was developed both theoretically and with practical realization, both for free lasing and Q-switched regime. To generate any desired pair of the given lines we employ a rotated prism (axis in the plane or perpendicular) Q-switcher that is completely non-sensitive of the different wavelengths. The scheme of experimental realization of the described two-line and two-mode laser is shown in Figure 13. The typical oscilloscope traces of simultaneous generation at two markedly different lines – 1.06 µm and 1.36 µm, obtained for conveniently chosen parameters of both resonators and lasing volumes are shown in Figure 13(b).

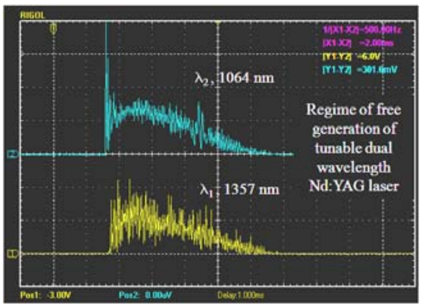


Figure 13(b). Simultaneous generation at 1.06 µm and 1.36 µm in free-running regime (for conveniently chosen parameters).

For the theoretical study we have adapted the rate differential equations system [Svelto, 1998] to obtain the optimal conditions for desired operation.

The theoretical considerations show the possibility to control the energy, time length of the pulses and delay between them, including also the possibility for simultaneous Q-switching operation - by conveniently chosen resonator parameters and parts of the lasing volumes. The experimental results are in agreement with the theory. As example in Figure 14 are presented the oscilloscope traces of Q-switched generation at the 1.06 µm and 1.36 µm (outputs ~1 MW).

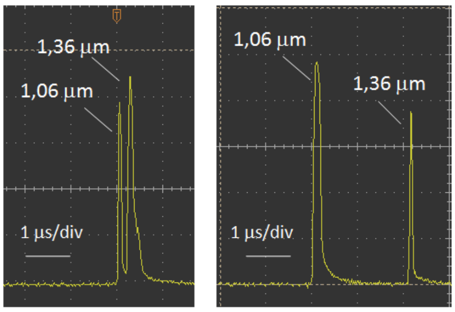


Figure 14. Experimental curves of temporal tuning of two wavelengths (the existence of a combination of parameters permitting simultaneous generation can be seen)

Note, that our rotating prism Q-switcher is very convenient for described operation due to its completely independence of the wavelength and its simplicity of operation.

The advantages of a developed laser in comparison with the system of two separated and coupled Nd:YAG lasers are: i) simple construction ii) essentially low cost and iii) increased efficiency due to the pumping of single active road

Such line-tunable and two-wavelength laser devices are of interest for applications in metrology, wavelength testing and study of non-linear effects in optical fibre, remote sensing and scientific works.

2.4 Generation of sub-nanosecond pulses implementing the original methodology with two-channel WDM-system based optical resonator

In detail, the original approach for realizing sub-nanosecond tunable laser is presented in our paper [Deneva, 2007]. The essence of the principle is to restrict the starting pulse-like generation with sub-nanosecond pulsations (~0.1 – 0.2 ns, “spikes”) to single pulsation by using an active mirror, which forces damping the competitive generation in the second selective channel. Theoretical analysis and experimental test showed the improvement of the shape and shortening the duration of the sub-nanosecond pulse by using our technique in comparison with known methods. The principle is clarified by the scheme shown in Figure 15. The typical pulses obtained by known techniques for separation of a single spike (Figure 16, left) and by our proposed technique (Figure 16, right) demonstrate the advantage of our approach.

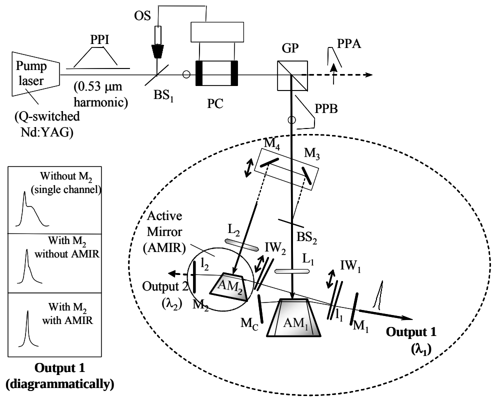


Figure 15. Set-up for selection of a single sub-nanosecond pulsation by active mirror in two-cannel cavity.

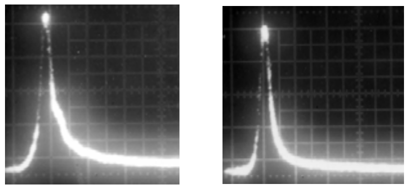


Figure 16. Typical oscilloscope traces (5 ns/div) of the optimized selected spike: left – for the known technique of competitive resonators and right- for our proposed AMIR- approach. Full confirmation of improvement of the selection by our predicted theoretical approach.

The generated sub-nanosecond pulses are of interest for testing system in optical communications, in systems for distance measurements, in scientific works and in remote sensing.

3 DEVELOPMENT OF LASERS WITH FIXED EMISSION FREQUENCY AT REFERENCE ATOMIC ABSORPTION LINE

A simple, all-optical technique for producing pulsed semiconductor laser light, spectrally narrowed and fixed at a chosen absorption atomic line, is realized and studied by us [Deneva, 2010]. The technique, which is not of laser locking type, is based on utilization of a conventional diode laser without any impact on its operation. For its implementation the diode laser output is fed to a modified Michelson interferometer, and controllable disturbing of phase and amplitude correlation between the interfering beams in the two arms of the interferometer is achieved by frequency scanning through a contour of reference absorption line of substance, introduced in one of the interferometer arms. Imbalance is produced by the absorption and the refractive index changes throughout the contour of the absorption line. The control of the imbalance is realized by variation of the optical path length of the other arm of the interferometer through an appropriate tilting of a glass plate introduced in this arm.

We have shown both by theory and experiment that under properly chosen conditions the spectrum of the obtained light partially overlaps the atomic line and has linewidth, comparable to the width of the absorption transition.

The set-up is given in Figure 16. A commercial single longitudinal mode pulsed diode laser (DBR type, model SDL-5702-H1) with emission line width of about 100 MHz was used as a light source. The wavelength of the selected mode of the diode laser was repetitively scanned (forward -backward) within ± 10 GHz (~ 0.0210 nm) around the 852.1 nm Cs absorption line ($6S_{1/2}$-$6P_{3/2}$ transition - a single absorption line within the scanned frequency region. The scanning was accomplished by the pump current modulation within ± 5 mA around 44.3 mA. The line width of the chosen Cs-transition was ≈ 0.92 GHz (0.0019 nm, FWHM). The diode temperature was kept at 17.9^{o}C with accuracy of ±0.1^{o}C. The diode laser beam, after passing through an optical isolation system (Faraday Isolator or a combination of a polarizer and a quarter-wave plate, as shown in Figure 16), impinged the entrance beam-splitter of a modified Michelson interferometer composed of the beam-splitter and wedged full reflecting dielectric mirrors M_1 and M_2. The beams reflected from M_1 and M_2 interfered at the beam splitter and formed the useful interferometer output (Output 1 in Figure 17).

A cell with atomic Cs vapour at room temperature (22^{o}C) was introduced to assure reference line in the first interferometer's arm between the beam-splitter and the mirror M_1 (at 852.1 nm Cs line).

If the wavelength of the selected mode remained outside the absorption line during the scanning of the diode driving current, the interference conditions did not change, and the Output 1 did not exist. Figure 18 shows the signals from the diodes PhD_1 and PhD_2; curve A corresponds to the Michelson interferometer Output 1 whereas the curve B depicts the signal from the diode PhD_2 (inverse polarity) that gives the absorption by the Cs line in the external reference Cs cell.

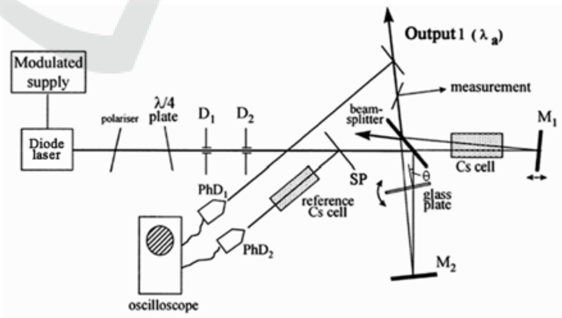


Figure 17. Experimental set-up for producing diode laser light spectrally fixed at the Cs absorption line.

When the laser diode wavelength fell into the contour of the chosen absorption line, the variation of the refractive index and the absorption changed the interference conditions. Thus the destructive interference was terminated and interferometer Output 1 appeared.

For the optimized conditions (Figure 18(c)), achieved by appropriate declination of the glass plate), the locked line is practically a single line with line width (~1.7 GHz, or 0.0035 nm) that is comparable to the absorption line width (0.9 GHz, 0.0019 nm) and overlaps the absorption by approximately 45%. The Output 1 is ~ 2 mW for ~10 mW laser diode emitted power. The performance is completely reproducible (~ hours).

The theory is in satisfactory agreement with the experiment and confirms the possibility of such kind of diode laser light generation.

The reported technique can be useful in a variety of spectroscopic applications when the target is a single transition which should be excited to monitor or separate a particular substance from a mixture of different substances.

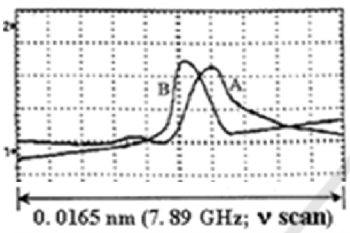


Figure 18. Spectrograms of the laser diode light emitted from Output 1 (curve A) and of the reference Cs cell (curve B; inverted signal). The exciting current is scanned.

Another simple system of spectral locking of the laser emission at the reference absorption line is also developed [Deneva, 2005; Gacheva, 2008]. Its principle is based on the disturbance of the competition between two injection-controlled generations in a two-channel resonator or two amplifications in single active medium. The injected light before the injection in one of the cannels or the amplifier input passes through a substance with the desired absorption line. This solution is clarified from the applied Figure 19.

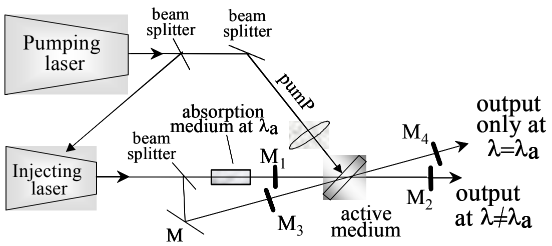


Figure 19. Frequency locking set-up.

The principle of our injection-locking technique is theoretically and experimentally demonstrated in our previous works [Keller, 2000; Slavov, 1998].

4 PRINCIPLE OF NEW INJECTION-LOCKING LINEAR AMPLIFIER OF AMPLITUDE MODULATED LASER LIGHT

At this point, we describe our principle of new injection-locking amplifier of amplitude modulated laser light using counter injection in a ring laser configuration. The last development includes the multichannel information laser light amplification (of the order of ~ 10^6 and more – from μW to W) with high linearity of the amplification. To amplify the injected in ring laser modulated laser light (simplest practical arrangement of the amplifier) we introduce counter-injection that compete with the modulated light and compel the amplification to follow exactly the modulation. The principle is clear from Figure 20 [Deneva, 1999].

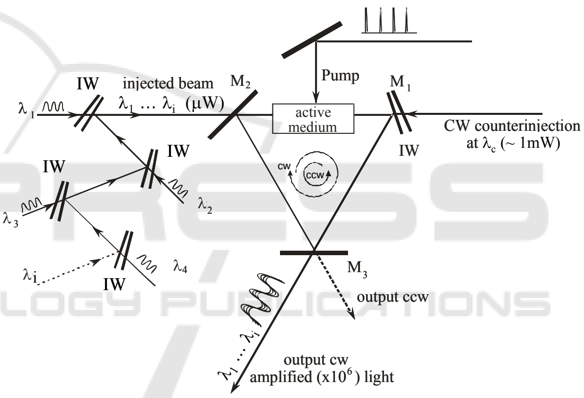
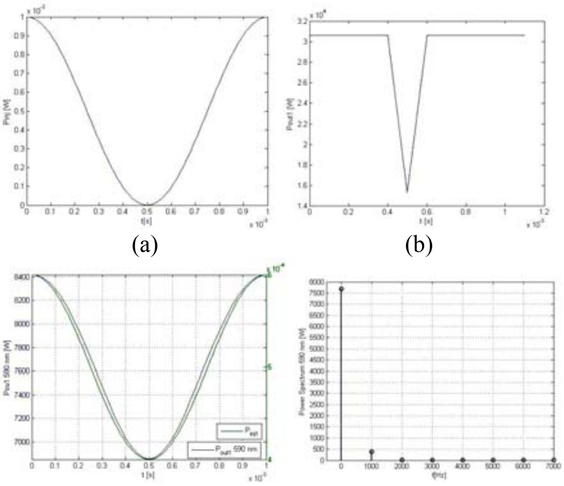


Figure 20. A new system for linear amplification based on injection–locking technique with counter- injection for linearization of the amplification (possibility – kW output power, ~ 10^6- 10^7 gain for injected modulated light of power ~ mW and μW)

We describe the action of the new ring counter-injection amplifier for the case of multichannel (at 5 wavelength channels) modulated laser beam amplification by adapting the rate of differential equations, adding the members that describe modulated injection and counter-injection.

Figure 21 gives typical calculation for single sine modulated wave. We have shown the ability of our amplifier to amplify simultaneously and linearly a number of injected beams with different frequency in a large range of ~ 800 GHz. The nonlinear distortions, defined by the harmonics relative power are less than 1 %. Such amplification is possible in very wide range of ~ 2400 GHz. The calculated curves of amplification for 4 wavelengths (communication channels) are shown in Figure 22.



(a) (b) (c) (d)

Figure 21. Example of operation of our ring-amplifier. (a) input signal, (b) and (c) – amplification without and with counter-injection, (d) Fourier spectrum of the (c).

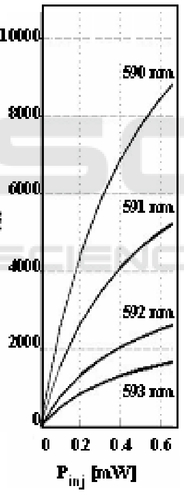


Figure. 22. The curves of simultaneous amplification of 4 injected lines in the presence of counter-injection (~1mW). It can be seen that the amplification is practically linear for injected power variation between 0.01mW and ~ 0.3mW. The amplification factor is ~ 10^5.

5 DEVELOPMENT OF OPTICAL TRANSISTOR

The new interferometer type device for light control by light (DLCL) uses on one hand the high sensitivity of the Fabry-Perot Interferometer (FPI) or IW to the losses in the interferometer's gap [Deneva, 2004]. Our original idea is to use the possibility to illuminate chosen volumes of the edge of interferometer's or wedge's gap in two quite different manners: i) through the interferometer mirrors (beam A- as shown in the figure); ii) directly into the gap (beam B). If the gap is full with saturable absorption medium and the mirrors are high reflective – e.g. 0.92–0.99, the beam A will affect the saturable absorber transmission only by transmitted small part through the mirror and respectively the FPI transmission will be drastically low for this beam. When the beam B illuminates directly the saturable absorber the effect of this illumination is very strong (no decreasing the illuminated light intensity by the mirror). Thus, with the low power beam B we can control in efficient manner (or to open and stop) the FPI or IW transmissivity for beam A. One first application of the new optical transistor will be to forms rectangular nano- and sub-nanosecond pulses as it can be understand from the Figure 23.

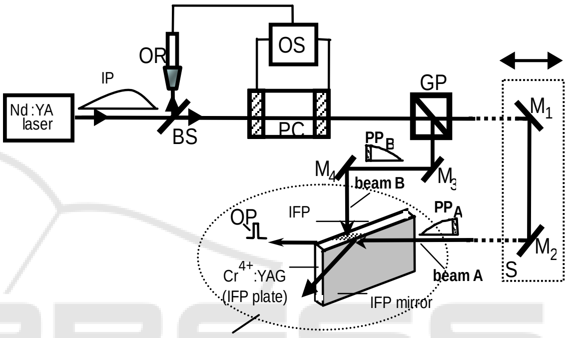


Figure 23. Schematic diagram of a Cr^{4+}:YAG- DCLC and of the experimental set-up for forming controlled duration rectangular laser light pulse. OR – optical receiver-synchronizer, PC-Pockel's cell, GP-Glan Prism, M_1,M_2-high reflectivity mirrors. The high speed switching PC (~ 1-2 ns), activated near the maximum of the input ~ 30 ns pulse, switches the polarization and the GP forms two spatially separated pulses that act in the described manner upon the Cr^{4+} gap FPI or IW.

Table 1: Example of transmissivity of new DLCL for Cr^{4+}:YAG as a saturable absorber [Nenchev, 2011]. The parameters of the DLCL are given in the table.

R of the mirrors	IFP or IW Thickness, mm	Illuminating beam energy density J/cm^2	Controlling beam energy dens. J/cm^2	T %
0.99	0.4	0.5 (0.5)	0 (0.1|)	3(8.6)
0.99	0.2	0.5 (0.5)	0 (0.1|	3(21)
0..99	0.1	0.5 (0.5)	0 (0.1)	9(40)
0.92	2.65	0.5 (0.5)	0 (0.1)	9(40)
0..52	20	0.5 (0.5)	0 (0.1)	1(10)

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