UNIVERSITY OF SZEGED
DEPARTMENT OF EXPERIMENTAL PHYSICS

SPECIAL EXCIMER LASERS

/PhD-thesis/

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I. SCIENTIFIC PRELIMINARIES, OBJECTS

Within the scope of an international project it fell to me to assemble a laser system, which meets the requirements of microlithography used in semiconductor production. In this period in the industry narrowband KrF lasers working at the 248nm wavelength were predominantly used for microlithography purposes. Common feature of these lasers is that they are based on single tuned oscillator. Because of certain physical and technical reasons, which will be made known in detail in the PhD thesis, it is practical to produce a laser system with a construction that differs from the foregoing ones, in which the optical signal of proper quality is provided by a low power oscillator optimized for this purpose, signal of which is further amplified by a high power amplifier. Taking the above into consideration,

I set assemble a „master oscillator-power amplifier” type laser system optimised for microlithography purposes as an aim.

Collaborating with the employees of the Chinese Institute of Atomic Energy I participated in the development of a high intensity (~10^{17} W/cm^2), long pulse (~60 ns) KrF excimer laser system. The final amplifier of the laser system is an electron beam pumped large aperture KrF laser, which – with three or six beam multiplexing technology – amplifies the pulses of a smaller KrF laser. During the researches it was a problem to preamplify the multiplexed seed pulses or to produce seed pulses of proper energy, independent of one another with low temporal uncertainty correlated to one another. Therefore

I set producing a KrF excimer laser system which is capable generating or amplifying three pulses independent of one another as an aim.

One possible generative process of the subpicosecond, high intensity ultraviolet pulses is to amplify the short, frequency converted seed pulses produced with solid state- or dye lasers in a KrF excimer laser. It is well-known that the extractable energy of an amplifier is proportional to the volume of the active medium, or rather participating effectively in amplifying the quantity of the excimer molecules excited with gas discharge depends on the homogeneity, and quality of the discharge. Our experiments showed us that the power of the preionization and the risetime of the electric pulse feeding the gas discharge considerably influences the homogeneity and the in time uncertainty of the discharge. As there is a necessity for KrF lasers suitable for amplifying short pulses in numerous research laboratory, therefore

I set development of homogeneous gas discharge pumped KrF excimer amplifiers optimized for amplifying short (subpicosecond) pulses pumped as an aim.

The majority of the above mentioned aims were successfully carried out. The achieved results contributed to the raise of the level of the research work connected to light-matter interaction in home and foreign research laboratories.

II. APPLIED TOOLS AND METHODS

The bandwidth of the FL2002E type narrowband dye laser used by me – according to the manual – is 1pm at a wavelength of 497nm. I checked the adjustment of the laser by measuring the bandwidth with the help of an IT51-30 type Fabry-Perot interferometer. The basis distance of this interferometer can be set with distance rings of different sizes and the parallelism of the mirrors can be ensured with plate laminated springs tightened with bolts. The parallelism of the mirrors was checked by this way: Increasing to some degree the aperture angle of the beam of a He-Ne laser with a negative lens I illuminated a little area of the ~30mm diameter mirror of the interferometer with the ~5mm diameter beam. I recorded the extracted interferogram with the help of a CCD camera. The mirrors are parallel when the surface of the interferometer is scanned with the He-Ne laser, the diameter of the observable interference rings does not change. Using this I set the mirrors parallel.

There was no spectrometer available that had sufficient spectral resolution to measure the bandwidth of narrowband ultraviolet laser pulses. Therefore, instead of directly measuring the spectrum I measured the coherence length of the laser pulse by a Michelson-interferometer made by me. In the interferometer I used a wedged quartz plate as a beam splitter. With this solution the interference caused by the beams reflected from the front- and back surface of the quartz plate can be avoided. During all optical measurements I used laser optical quality mirrors, lenses and prisms. During the measurement of the - very little - beam divergence of the narrowband KrF laser I came to the conclusion that aberrations of conventional lenses falsify the measurement as I got different results with different lenses of focal length. Therefore I focused the beam with a parabolic mirror instead of a lens.

I accomplished the measurement of rapidly changing high voltage with a very precise broad bandwidth (100MHz) measuring system consisting of a voltage divider and an oscilloscope.

I measured the length and the delay of the laser pulses with a Thorlabs 410 type fast 1ns risetime photodiode and with a 350 MHz bandwidth oscilloscope.

I recorded the oscillograms and interferograms with the help of a measuring system consisting of a computer and a picture digitalizer.

III. ACHIEVEMENTS

1. ***I have developed a new hybrid dye-excimer laser system which – integrating the advantageous properties of each laser of the laser system - is suitable to generate laser pulses of small bandwidth (~0.2 pm) and a pulse energy of ~300 mJ at a wavelength of 248nm [1].***

   In the laser produced by me an excimer laser pumped dye laser working in the visible provides the seed pulse which after frequency duplication is amplified in another excimer laser. The greatest advantage of this kind of setup is – contrary to narrowband excimer lasers used in the industry – that oscillators working in visible spectrum domain are easier to be produced because of several technological and physical reasons. Additional advantage is that the length of the dye laser produced in this way – in case of the same pulse length – can be smaller than that of an excimer laser, which results in narrower bandwidth. During the period of my experiments the bandwidth of the most up-to-date KrF excimer lasers used in the industry was ~0,4pm – 0,5pm [5,6]. This is about two times the bandwidth of the laser made by me.

2. ***I have engineered or rather built two electric circuits which are capable to compensate the leakage current of magnetic switches used in excimer lasers pumped with circuits applying series magnetic switch. These circuits improve the homogeneity of the discharge and have the practical advantage that they can be installed in excimer lasers anytime [2].***

If we increased the stored energy in the medium of the amplifying excimer the amplification short pulses would be more effective [7,8]. Feeding the gas discharge with low risetime voltage pulse, homogeneity of the gas discharge, the volume of the active medium and therefore its stored energy can be increased [9,10]. Disadvantageous feature of the magnetic switch working by principle of magnetic saturation is that in opened state its impedance is limited, therefore even in this state there is leakage current in it [11]. Attaining this current in the excimer laser to the cathode feeding the gas discharge, then it causes voltage increase, the so called „prepulse” before getting the magnetic switch in closed state and starting the gas discharge exciting the excimer. This prepulse in contempt of precise preionization produces ion channels in the active medium, deteriorating the homogeneity, or rather the quality of the gas discharge especially in case of krypton-fluoride [9,10]. One of the circuits solutions proposed by me feeds current with a direction reverse to that of the prepulse into the cathode and compensates it in this way. The other circuit changes the voltage of the anode at the same rate as the leakage current does it to the voltage of the cathode, then it changes the polarity of the anode – this is called differential pumping. With this method not only the effect of the prepulse can be eliminated, but the peak voltage between the electrodes can also be increased. A laser made in the laboratory utilizing the method of differential pumping works in the laboratory of the Department of Physics at the University of Chicago.

3. ***I have developed a new preionization method – assisted with pre-preionization - which increases the homogeneity of the gas discharge by significantly increasing the effectiveness of the preionization in excimer lasers. With the help of this new preionization method the conventional excimer amplifiers – applying automatic preionization - can be modified to be more capable of amplifying subpicosecond pulses [3].***

With the help of stronger preionization the homogeneity of the gas discharge, the volume of the active medium and therefore the stored energy in it can be increased [10]. In the KrF excimer lasers used by us the preionization is ensured with spark gaps integrated into the discharge chamber. For the sake of stronger preionization I enlarged the preionization spark gaps from the original 0.8mm to 3mm. My experiments however resulted that with the advantages produced by the enlarged spark gaps the uncertainty of the preionization in time increases which also increases the uncertainty of the exciting discharge in time. This can be disadvantageous, for example when the amplifier should be synchronised to an oscillator.

This can be avoided by, preionizing the preionization spark gaps (we call this „pre-preionization”) which decreases the uncertainty of the discharge in the amplifier in time. Notice that the pre-preionization spark gaps are also in the discharge volume. I worked out their electric feeding with two different electric circuits. We apply the innovations described briefly in the 3. and 4. theses built into Szatmári-type subpicosecond, off-axis, hybrid dye-excimer or solid-state-excimer lasers. The same lasers are used in the laboratory of the Department of Physics at the University of Chicago and in the Laser Laboratory of Göttingen (Germany).

4. ***I have developed a new electric circuit which is able to pump excimer lasers with three separate discharge chambers. This laser system has the unique feature that it has one thyratron and one special "distributed" magnetic switch working by the principle of magnetic saturation, therefore it can pump separate gas discharges correlated to one another with low jitter and high delay. Applying this circuit, I have built a KrF laser with three separate channels, which is capable of amplifying three identical pulses of 20-20 ns delay, or, in an oscillator mode, of generating three pulses, each having more than 600 mJ energy. The relative jitter of the pulses is in the range of 1 ns [4].***

a) During the construction of the excimer laser with three separate discharge chambers I experienced that the traditional pumping circuits driven with a magnetic switch are not suitable to pump three separate discharge chambers if our purpose is to make a delay between the discharges which is more than ~10% of the rise time of the pumping voltage pulse. According to my experience if in this circuit the desired delays are produced by air-cored inductances –as it is done in the industry –, the amplitudes of the exciting pulses connected to certain discharges are not equal to one another. I suppose that this can be explained with ‘parasitic oscillations’ forming between discharge chambers. Suppressing these oscillations is possible if the impedance of the magnetic switch is decreased and the inductances, which are responsible for switching and delaying are integrated into the magnetic switch. My computer simulations show that an optimal ratio of the inductances responsible for switching and delaying exists, if so each discharge gets the same electric energy. Utilizing my experiences, I have engineered a KrF laser with three separate discharge chambers, which is now used as a preamplifier of an electron beam pumped excimer laser in the High Energy Laser Laboratory of the Chinese Institute of Atomic Energy.

b) According to my experience in analysing and optimizing the laser with three discharge chambers, if we wish to delay the gas discharges on a large scale - by tens or hundreds of nanoseconds -, it is practical to apply a new circuit. In this new circuit the switching is done with single thyratron and – in the case of a laser having two discharge chambers – two magnetic switches. The feature of magnetic switches that saturating them takes tens or hundreds of nanoseconds can be utilized to delay the pumping pulse. This solution has the advantage that a magnetic switch in closed state – because of its geometrical size – does not increase the inductance of the pumping circuit considerably, therefore the rise time of the pumping pulse remains low. This has an advantage over generating the delay with air-cored inductances. This is a necessary condition of pumping the excimers effectively. Utilizing my experiences, I have further developed the discharge circuit of the dye-excimer subpicosecond laser system of the High Intensity Laser Laboratory headed by prof. Sándor Szatmári.

IV. POTENTIAL UTILIZATION OF THE ACHIEVEMENTS

The achieved results were directly utilized in many laboratories. For example, KrF laser with the three discharge chambers is applied as a part of a high energy excimer laser system in the High Energy Laser Laboratory of the Chinese Institute of Atomic Energy. The KrF lasers having discharge circuit optimized for amplifying subpicosecond signals are now used in the Laser Laboratory of Göttingen and in the laboratory of the Department of Physics in the University of Chicago.

V. PUBLICATIONS THAT THE THESIS AND THE REFERENCES ARE BASED ON

Own publications

[1] **J. Bohus**, S. Szatmári: *An alternative approach for microlithography light source.* Applied Physics B, **80** (4-5) p.577 (2005)

[2] S. Szatmári, **J. Bohus:** *Differential pumping scheme for discharge pumped excimer lasers.* Rev. Sci. Instrum. **77**, 045105 (2006)

[3] S. Szatmári, Janicskó J., **J. Bohus**: Two-step preionization scheme for discharge-pumped KrF excimer lasers (Rev. Sci. Instrum.)

[4] S. Szatmári, **J. Bohus**, G. Zhixing, X. Tang, N. Wang: *Three-channel KrF laser with distributed magnetic switch-based charging circuit.* Rev. Sci. Instrum. **77**, 115106 (2006)

Referenced publications

[5] Cymer: *ELS-6010 KrF excimer laser.* http://www.cymer.com

[6] Lambda Physik: *New Novaline K2005 – The perfect match for high NA DUV scanners.* http://www.lambdaphysik.com

[7] S. Szatmári: *High –brightness ultraviolet excimer lasers.* Appl.Phys. B, **58,** p.211 (1994)

[8] Taylor A.J., Tallman C.R., Robrtes J.P., Lester C.S., Gosnell T.R., Lee P.H., Kyrala G.A.: *High intensity subpicosecond XeCl laser system*. Opt. Lett. **15,** p.39 (1990)

[9] Jeffrey I. Levatter, Shao-Chi Lin: *Necessary conditions for the homogeneous formation of pulsed avalanche discharges at high gas pressures.* J.Appl.Phys. **51** (1) p.210 (1980)

[10] S.Sumida, K.Kunitomo, M.Kaburagi, M. Obara, T. Fujioka: *Effect of preionization uniformity on a KrF laser.* J.Appl.Phys. **52** (4) p.2682 (1981)

[11] W.C. Nunnally: *Magnetic switches and circuits.* Los Alamos laboratory report LA-8862-MS (1982)