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Device for Periodic Modulation of Laser Radiation

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In this paper we consider a new type of mechanical device for periodic modulation of laser radiation. The modulating unit consists of two phase diffraction gratings with a rectangular profile, one of which moves relative to the other. The output beam of radiation in this device can be either a zero-order beam of diffraction, or one of the first orders of diffraction. The results of numerical simulation of output waveforms are presented. In the first order, we obtain a sinusoidal form of output power modulation with an efficiency of up to 40 percent. Optimal parameters of the phase diffraction gratings are calculated. Modulation produced in the zero order of diffraction has an impulse form with an efficiency of about 80–90 percent. The specific shape of the pulses in the zero order of diffraction depends on the distance between the two gratings. The results of numerical calculations and experimental studies are in good agreement. A special advantage of this type of modulator is the possibility of increasing the frequency of mechanical modulation of the laser beam to hundreds of kHz. The results of experimental studies of the characteristics of the scheme under consideration are presented. The device makes it possible to obtain modulation frequencies up to hundreds of kHz with a harmonic waveform in the first orders of diffraction and periodic pulses in the zero order.

Key words and phrases: modulation of a laser beam, an optical modulator, diffraction gratings, double diffraction on phase gratings

1. Introduction

Optical choppers are widely used during physical experiments. Optical chopper is a rotating disk punctuated with holes or slits. Since this type of laser modulator is mechanical in nature, the maximum frequency is limited to the several kHz. In addition, when the laser beam intersects the borders of holes, diffraction effects occurs, which distort a shape of the output beam. The other type of mechanical laser beam modulator described in [1] allows obtaining up to 100% modulation of laser radiation power, but the maximal frequency of modulation is also low.

In this report, we present results of investigations of the device where laser beam modulation occurs as a result of sequential diffraction by two phase diffraction gratings, one of which is being moved relatively to the other one in the direction across grating lines. There are specific diffraction gratings which have a rectangular "meander" type profile formed by a relief on a transparent substrate used in this device.

With applying of this device it is possible to increase the frequency of modulation of the laser beam up to hundreds kHz. In the special case, when we use the first diffraction order as output beam, it is possible to obtain its power modulation according to the harmonic law. When we use the zero diffraction order as output beam, it is possible to get the modulation of the output beam in the form of periodic pulses of a specific shape with a peak power close to the radiation power at the input of the device.

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2. Theoretical Analysis

The modulator scheme is shown in Fig. 1. The device includes a laser 7, a modulating unit (1–4, 6) and a spatial filter 5. The modulating unit consists of two transparent disks 1 and 3. There are two identical circular relief diffraction gratings (DG) 2 and 4 of the same period Λ, located on the periphery of disks surfaces at distances R_G from the centres of these disks. Disks are located in parallel planes at a small distance from each other. The distance l_z between the DGs, which are located on the surfaces of the disks, facing each other, must satisfy the condition: $l_z \ll \Lambda^2/\lambda$, where λ is the laser wavelength. One of the disks is rotated by the motor 6 relative to the second disk, making **n** revolutions per second (rps).

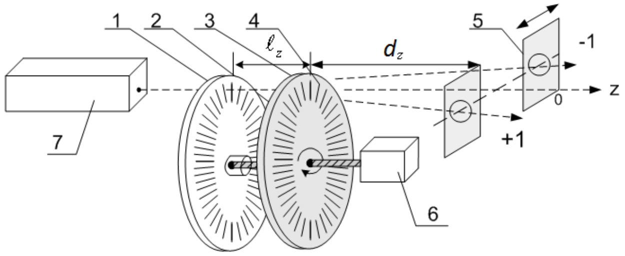

Figure 1. Schematic diagram of the laser light modulator with modulating unit containing two DGs

The relief has a specific form of the "meander" type, with the width of the protrusions equal to the width of the grooves. The lines of the relief of the DG are located along the radial directions to the center of the disk. The optimal depth of the relief of the DG, at which the modulation in the zero and in the first orders has the maximum amplitude, is calculated by the following formula:

$$h_{\mathrm{OPT}} = \frac{\lambda}{4(n_g - 1)}, \tag{1}$$

where n_g is the refractive index of the substance of which the relief is made. When the depth of the relief is equal to h_{OPT}, the depth of optical wave front phase modulation is equal to $\Delta\varphi = \pi/2$, and the amplitude of the optical wave spatial phase modulation (SPM) is $\Phi_{\mathrm{M}} = \Delta\varphi/2 = \pi/4$.

The interaction of optical wave with the system of two diffraction gratings, as shown on the Fig. 2, was considered in [2]. This analysis shows that the radiation power in diffraction orders depends on several parameters: the distance between the DGs, the displacement of one grating relative to the other one in the $0x$ direction, as far as the amplitude and shape of the SPM which obtained by the optical wave after propagating through each of these phase type gratings.

As follows from theoretical analysis we can get the best results, when we use DG of the special rectangular meander profile, since **there are no even diffraction orders** in the diffraction spatial spectra of these DGs. Only in this special case periodical oscillation of the output optical beam power of the first orders of diffraction as a result of one of the DGs moving relative to the other occurs according to a harmonic law. Power oscillations of the zero order will be periodical also. But these oscillations would not be purely sinusoidal. When the optimal depth of the gratings, h_{OPT} is used, the highest modulation efficiency is obtained. At a depth of each grating equal to h_{OPT}, and with a normal incidence of the laser beam on the DGs, the dependence of the intensity coefficient in the first diffraction orders on the displacement of the DG across the grating lines is expressed by formula [1]:

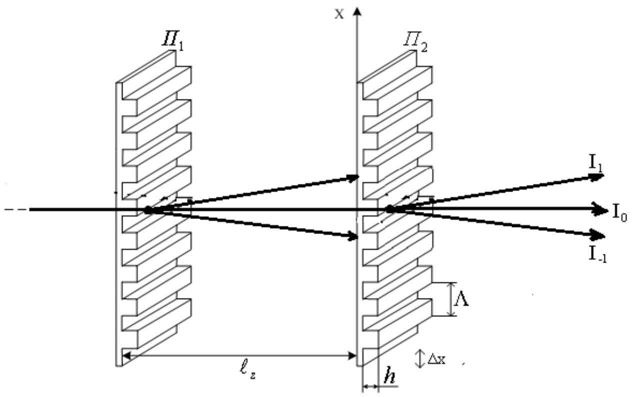

Figure 2. Diagram showing an optical wave propagates through a system of two DGs

$$I_{\pm 1}(x) = \frac{2}{\pi^2} + \frac{2}{\pi^2}\cos\left(\frac{2\pi}{\Lambda} x m L\right), \tag{2}$$

$$L = \pi \frac{\lambda}{\Lambda^2} l_z \text{ — the distance parameter.}$$

The intensity coefficient in the zero order of diffraction is described by a more complicated formula which contains infinite series of harmonics [1]:

$$\begin{aligned} I_0 = \frac{1}{3} - \frac{4}{\pi^2}\sum_{k=0}^{+\infty} \frac{\cos\left((2k+1)^2 L\right)}{(2k+1)^2} \cos\left((2k+1)\left(\frac{2\pi}{\Lambda}x\right)\right) + \\ + \frac{8}{\pi^4}\sum_{k=0}^{+\infty}\sum_{k'=0}^{+\infty} \frac{\cos\bigl(4(k^2 - k'^2 + k - k')L\bigr)}{(2k+1)^2(2k'+1)^2} \cos\left(2(k'-k)\left(\frac{2\pi}{\Lambda}x\right)\right) + \\ + \frac{8}{\pi^4}\sum_{k=0}^{+\infty}\sum_{j=0}^{+\infty} \frac{\cos\left(2(k+j+1)\left(\frac{2\pi}{\Lambda}x\right) + 4(j^2 - k^2 + j - k)L\right)}{(2k+1)^2(2j+1)^2}, \quad k \neq k'. \end{aligned} \tag{3}$$

Power of the beam radiated to the order of diffraction with the number n ($n = 0, 1, -1$) is related to the intensity coefficient and to the radiation power P_{in} measured at the input of the device, by formula:

$$P_n = \eta I_n P_{\text{in}}. \tag{4}$$

Here η is coefficient of effective use of power, taking into account radiation losses in the optical scheme due to reflection and absorption. As follows from formula (2), the output power in the *first diffraction order* varies according to a harmonic law from zero to a maximum value which is equal to $P_{1\,\max} = (4/\pi^2)\eta P_{\text{in}}$. The intensity of the *zero diffraction order* also varies with a period equal to Λ. The **shape** of the intensity dependence on the displacement of DG is similar to pulse shape. The shapes of these pulses are changed in a complex way with changing of the parameter L. Dependences of power of different diffraction orders on the displacement of the DG, calculated by formulas (2) and (3) are presented in Fig. 3a. The amplitude of modulation of the zero order beam power reaches the value $P_{0\,\mathrm{max}} = 0.9\eta P_{\mathrm{in}}$ (provided parameter $L = 0.05$).

For the purpose of experimental investigation of these dependences the special setup with use of two phase gratings of a rectangular profile of period equal to $\Lambda = 200$ μm and with relief depth which was close to the optimum have been fabricated. One of the gratings was stationary. The second one was installed parallel to the first grating on the moving platform. The second grating was driven by a micrometric screw in the direction across the grating lines. The displacement step was 10 μm. In addition, the design allowed changing the distance between two DGs. A He-Ne laser with a wavelength $\lambda = 0.63$ μm was used as a source of coherent radiation. Diffraction orders intensities were measured by a photodiode with use of reverse bias. Experimental dependencies of radiation intensities in the diffraction orders on the displacement of the DG are presented in Fig. 3b.

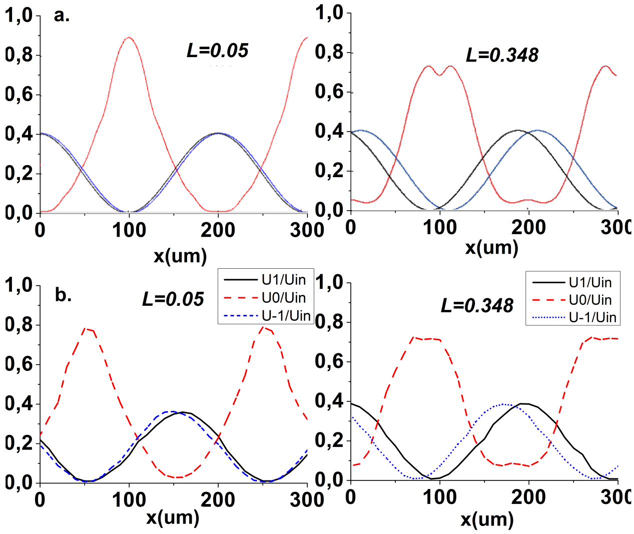

Figure 3. Calculated (a) and experimental (b) power dependences in the zero and first orders of diffraction on the displacement for different values of the distance parameter L

As can be seen from comparing Fig. 3a and 3b, the shapes of experimental curves are in a good agreement with the calculated ones. When one grating is being moved in the direction of the $0x$ axis at a constant speed, periodic modulation of the diffraction orders power in dependence of time would be observed. In the first orders of diffraction, the modulation shape will be harmonic. Also one can see that phases of the oscillations in the first and minus first orders of diffraction depend on the distance between two gratings. In the zero order of diffraction the shape of periodic modulation looks like pulses, which amplitudes are about from $0.9\eta P_{\mathrm{in}}$ to $0.7\eta P_{\mathrm{in}}$.

3. Experimental Investigation of the Modulator Setup

Experimental setup was built according to the scheme shown in Fig. 1. Disk sectors with gratings were manufactured using photolithography and chemical etching of glass. The DG period, measured at a distance of 3 cm from the center of the disk, was 150 μm. The amplitude of the SPM of DG was calculated from the measured ratio of the powers of the zero and the first diffraction orders [3]. By measuring results the amplitude of SPM was close to $\Phi_{\mathrm{M}} = \pi/4$, in practice $\Phi_{\mathrm{M}} = (42\boldsymbol{\nabla}\cdot 43)^\circ$. The stationary grating was fixed on the path of the laser beam. The movable grating was installed in the hole on the surface of the disk. The disc was driven by a DC motor. Gratings were installed in parallel at a distance of about 1 mm. It was possible to tune the position of one of the disks in order to ensure the parallelism of the grating lines. Photodiodes with load resistors were installed in diffraction orders. Reverse bias voltage was connected to photodiode. In this case, the voltage across the load resistor is proportional to the power of the radiation incident on the photodiode. The shape of the output signal was recorded using an oscilloscope with a signal recording function.

The experimental modulation characteristics are presented in Fig. 4. The dependence was normalized to the voltage measured on the photodiode load resistor when a laser beam was directed onto the photodiode, with correction of this value taking into account reflection losses. The modulation curves are very close to the calculated ones.

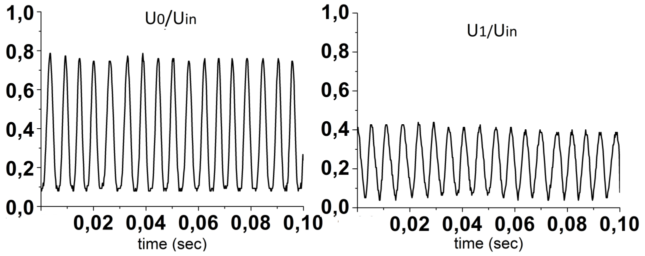

Figure 4. Experimental dependencies of output beam intensities on time. Rotation speed was equal to $n = 0.15$ rps, modulation frequency was $F = 190$ Hz

When the disk rotates, the linear displacement speed of the moving grating relatively to the stationary one is equal to $\nu = 2\pi Rn$. The oscillation frequency is equal to $F = \nu/\Lambda = 2\pi Rn/\Lambda$. For $R = 3$ cm, with $n = 0.15$ rps and $\Lambda = 150$ μm we get calculated value: $F = 188$ Hz, which is very close to the experimental value of the modulation frequency $F = 190$ Hz. With increasing rotation speed of the disk to 100 rps, with the same grating parameters, the modulation frequency will be increased up to $F = 125$ kHz.

4. Conclusions

The method of laser beam modulation with use of the system of two diffraction gratings is investigated theoretically and experimentally. Modulation frequencies of the hundred of kHz domain with the use of mechanical type driver are possible. Harmonic type shape of the output beam modulation can be obtained in the first order of diffraction. Pulse type modulation can be obtained in the zero order of diffraction. Zero-order modulation with amplitude $P_{0\,\max} = 0.75\eta P_{\text{in}}$ and harmonic modulation in the first diffraction order with amplitude $P_{1\,\max} = 0.35\eta P_{\text{in}}$ at a depth of the gratings close to the optimum was demonstrated.

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Устройство для периодической модуляции лазерного излучения

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В настоящей работе рассматривается новый тип механического устройства для периодической модуляции лазерного излучения. Модулирующий блок состоит из двух фазовых дифракционных решёток с прямоугольным профилем, одна из которых перемещается относительно другой. Выходным пучком излучения в этом устройстве может быть либо пучок нулевого порядка дифракции, либо один из первых порядков дифракции. Приводятся результаты численного моделирования форм выходных сигналов. В первом порядке мы получаем синусоидальную форму модуляции выходной мощности с эффективностью до 40 процентов. Рассчитаны оптимальные параметры фазовых дифракционных решёток. Модуляция, производимая в нулевом порядке дифракции, имеет импульсную форму с эффективностью около 80–90 процентов. Конкретная форма импульсов в нулевом порядке дифракции зависит от расстояния между двумя решётками. Результаты численных расчётов и экспериментальных исследований находятся в хорошем согласии. Особым преимуществом этого типа модулятора является возможность увеличения частоты механической модуляции лазерного луча до сотен кГц. Приводятся результаты экспериментальных исследований характеристик рассматриваемой схемы. Устройство позволяет получать частоты модуляции до сотен кГц с сигналом гармонической формы в первых порядках дифракции и периодическими импульсами в нулевом порядке.

Ключевые слова: модуляция лазерного пучка, оптический модулятор, дифракционные решётки, двойная дифракция на фазовых решётках

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