Efficient material treatment by axi-symmetrically polarized laser radiation

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Abstract. Recent years the increased interest is to the problem of interaction of nontraditionally polarized laser radiation with condensed media. The experiments with axisymmetrical polarization attract more attention. The peculiarities of interaction of axisymmetrical laser radiation with condensed matter are considered in framework of universal polariton model. It is shown that more effective is interaction of radially polarized laser radiation with surface active media. The optical schemes for efficient material treatment by radially polarized radiation are sketched.

For the increasing the efficiency of material treatment by laser radiation different approaches are known [1]. Conditionally they can be divided into two types: a) using different geometry of materials irradiation and b) using excitation of surface electromagnetic waves (waveguide modes, surface polaritons, localized surface plasmons, channel and wedge polaritons) at material interfaces and dissipation their energy in materials. Below the approach based on the surface polariton’s excitation and their energy dissipation in materials will be considered. The consideration will be made on the basis of universal surface polariton model [2].

It is known that under the interaction of linear polarized laser radiation with materials having surface-active interfaces the linear gratings may be produced the grating (g) the periods of which are of the order of \( \lambda \) at near normal incidence, \( d = \frac{\lambda}{\eta} \) and orientation \( g \parallel E \), where \( \lambda \) is the wavelength of incident laser radiation and \( \eta \) is the real part of refractive index of surface polariton for considered boundary. For non normal incidence the angular dependence of the period arises.

The application of laser radiation with nontraditional polarization (for instance, axisymmetrical polarization) put forward the question about the resonant gratings parameters arising in framework of polariton model.

Let us consider the action of a radially polarized radiation (RPR) with selected direction of polarization \( \varphi_0 \), where \( \varphi = \varphi_0 \) is the angle characterizing (local) direction of the electric field vector of the incident wave. It is known that the SPP frequency is equal to that of the laser radiation, while its wave vector \( k_s \) is determined by the law of conservation of momentum (quasi-momentum) [3]:

\[
k_s = k_0 + mg.
\]
where \( k_t \) is the tangent component of the wave vector of laser radiation, \( g \) is the vector of the resonance grating that allows conversion of laser radiation to the surface polaritons (SP), and \( m \) is the order of diffraction. At normal incidence of radiation, \( k_t = 0, k_s = g \), and

\[
g \parallel k_t(\phi_0) .
\]

The induced grating is characterized by orientation (2) and period

\[
d = \frac{2\pi}{|k_s|} = \frac{\lambda}{\eta} .
\]

Figure 1. Distribution of (a, c) intensity and (b, d) corresponding microstructures formed under the influence of a train of femtosecond laser pulses with (a) radial and (c) azimuthal polarization on the surface of silicon [4].

If \( \phi \in [0, 2\pi) \), i.e., takes all possible values, there appears a grating in the form of axial ring structures with a period determined by (3). Hence, the resonance grating corresponding to interference of the radially polarized laser radiation with driven by it SPs represents axisymmetric ring structures with a period determined by (3). Based on similar arguments, it can readily be shown that the azimuthally polarized laser radiation causes formation of radial structures of damage.

The experimental results well support the suggested approach for ultrashort pulse duration radiation for semiconductors (monocrystalline silicon) [4, 5], dielectrics (quartz glass) [6] and metals (brass, stainless steel) [7-8] under the action of pulses series of radial and azimuthal polarization, see Figures 1 and 2. In listed examples the effect was observed under the action of ultrashort laser pulses and for surface plasmon polaritons. The effect can also exists for longer pulse durations and for surface phonon polaritons. Really, the formation of circular gratings was observed under the interaction of series of chaotically polarized pulses of TEA CO\(_2\) laser radiation (\( \lambda = 10.6 \mu m \)) with quartz glass (frequency range of reststrahlen band). Possibly, in this case the radiation polarization direction chaotically changes its polarization direction from pulse to pulse. The period of the grating was near 9 \( \mu m \).

Take attention to the peculiarity of dynamic structures with appear under the action of radially polarized laser radiation. The circular grating has a resonant period and directions of excited surface plasmon polaritons are perpendicular to the local grating direction. Hence part of the SPP are focused.
by surface grating into the spot diameter of \( d = \frac{\lambda}{\eta} \) and another part is defocused and decays out of irradiated area, see Figure 3. So we have dynamic focusing of radiation which transfers SPP’s energy to the spot center. In addition the radially polarized radiation itself is focused to the spot of smaller size [9] than linear polarized one. This results in effective reducing the size of overall other all energy dissipation and efficiently increases the power density of incident radiation.

**Figure 2.** Ordered microstructures formed on the surface of fused silica by a train polarized radiation; (c, d) azimuthally polarized radiation. The power densities in Figs. 2b and 2d are 1.6 times higher than in Figs femtosecond laser pulses (\( \lambda = 775 \) nm, \( \tau = 200 \) fs): (a, b) radially. 2a and 2b [6].

In universal polariton model the resonant grating \( g \) (for linear, circular and axisymmetrically polarized radiation) arises from small ones presented in the whole spectrum of initially rough surface during the series of laser pulses due to the positive feedback via grating amplitude (or value of dielectric permittivity module change). To increase the efficiency of material treatment we suggest the artificially creating resonant grating which will transfer incident radiation into SPP’s. For **linear** polarized laser radiation the interference of two laser beams creates the artificial grating \( g_{\text{inter}} \) which transforms incident radiation of one or two beams into SPP’s [11]:

\[
g_{\text{inter}} = g_{\text{res}}. \tag{4}
\]

One of possible examples of such grating, symmetrical incidence of laser beams and transformation of radiation from each beam is shown on Figure 4. In this case interference grating period is \( d_{\text{inter}} = \frac{\lambda}{2 \sin \theta} \) and \( d_{\text{res}} = \frac{\lambda}{n \sin \theta} \). So using equation (4) for grating modules we obtain:

\[
\theta = \arcsin \frac{n}{\lambda}. \tag{5}
\]

Here \( \theta \) is the incidence angle for the case of symmetrical incidence, see Fig.4. In this case the treated surface is placed in the place of maximal beams overlapping, see Fig.4. For the case \( n = 1 \) we have \( \theta \approx 27^\circ - 28^\circ \). The practical realization of symmetrical two beam scheme will be a simple use of
Fresnel bi-prism with appropriately chosen prism’s angle. Note that it is well known that by optimizing the value of the resonant grating depth near 100% of incident laser radiation will be absorbed by the boundary with surface active media [12].

**Figure 3.** Schematic illustration of formation of an axisymmetric ring resonance grating on the surface of a condensed medium by radially polarized laser radiation; the grating converts incident radiation into surface polaritons that are focused onto the structure center. The inset shows polarization of laser radiation in the beam cross section [10].

This method can be used for resonant grating production of higher quality over large area via sample translation in the direction of SPP propagation.

Such approach can be applied to the case of radially polarized laser radiation. In this case we must create the circular resonant grating. The axicon optical element with proper chosen angle $\alpha$ (see equation (5)) can be used to create the circular grating, see Figure 5. Note that it will be desirable to take in mind the influence of the produced periodical surface modulations on the SPP’s dispersion relation and fine alignment of axicon angle ($\beta$) in limits of half-width of resonant absorption line of SPP. The radially polarized laser radiation which illuminates the axicon can be obtained by different methods, for instance, with the help of the $\beta$-plate.

**Figure 4.** Optical scheme for artificial interference resonant grating formation by symmetrically incident p-polarized coherent laser beams and subsequent SPP excitation by each of beams via this dynamic grating.
Figure 5 shows a novel simple technique for generating radial polarization light from a linearly or circularly polarized laser light [14]. A birefringent plate of predetermined thickness is placed in between a telescope module. Light rays of a convergent beam or divergent beam travel different optical paths lengths when they transmit a birefringent plate. The light rays at the central part of the beam travel shorter distance than those at the edge through a birefringent material. This result in shift in electric field vector in the plane of the beam cross section is parallel to the radial direction.

**Figure 5.** Optical scheme for materials treatment by radially polarized radiation. 1 – axicon, 2 – sample. The inset at right shows enlarged view of dynamic (residual) grating formation in irradiated zone. Note that axicon can be joint with β–plate. In this case the joint element must be irradiated by linear polarized radiation. When the possibility arises for material treatment by radially and azimuthally polarized radiation.

Figure 6 shows a novel simple technique for generating radial polarization light from a linearly or circularly polarized laser light [13]. A birefringent plate of predetermined thickness is placed in between a telescope module. Light rays of a convergent beam or divergent beam travel different optical paths lengths when they transmit a birefringent plate. The light rays at the central part of the beam travel shorter distance than those at the edge through a birefringent material. This result in shift in electric field vector in the plane of the beam cross section is parallel to the radial direction.

**Figure 6.** Polarization converter with birefringent plate in between a Keplerian telescope.

The influence of the (partially) radially polarized continuous wave CO\textsubscript{2} laser radiation on the metal cutting velocity has demonstrated an increase in cutting velocity up to 1.4 times in comparison with circular polarization [14, 15].

A diode pumped solid state Nd: YAG laser at 355 nm wavelength of 11 W average power (nanosecond range pulse duration) was used to provide the linearly polarized laser beam. The pulse repetition rate was from 50 kHz to 100 kHz. Then the scheme with birefringent plate was used it results in smaller ablation spot size on silicon plate and increased ablation depth due to shift the polarization state to radial. So radially polarized beam increases the machining efficiency by (40 \pm 100) % and reduces the focal spot size by more than 30 % [13]. In the laser pulse silicon was melted and achieves the property of surface-active media.
In the regime of Q-switching the preliminary results of metal drilling by radially polarized radiation show a two-fold increase of the drilling speed [16]. Depending on the optical properties of the metal either radial or azimuthal polarization shows the best efficiency. For steel, a comparison to linear or circularly polarized laser radiation indicates that doughnut–shaped beam with azimuthal polarization is more energy efficient to produce holes of the same diameter and depth.

Note that one must take into account the further input to the effective material absorptivity from additional excitation by polarized laser radiation of channel and wedge surface plasmon polaritons, especially for ultrashort pulses [17].

In conclusion, the formation of circular grating and radial microstructures have been theoretically predicted in framework of universal polariton model and verified by experiments with series of ultrashort laser pulses and materials having different physical properties: semiconductors, dielectrics and metals. It was shown that radially polarized laser radiation more effectively interacts with surface active media. Number of examples has illustrated the efficiency effectiveness of interaction for continuous wave radiation, series of nanosecond and femtosecond pulses in cutting and drilling processes for metals, semiconductors and dielectrics. The optical schemes were suggested for further radially polarized laser treatment enhancement.

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