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# On the nature of laser polariton tracks in soap films

A.V. Startsev, Yu.Yu. Stoilov

***Abstract*. The results of the study of narrow laser tracks in soap films with the divergence below the diffraction-limited value are presented, and the mechanism of formation of narrow channels (spatial polariton solitons) based on laser dielectrophoresis in films is proposed.**

***Keywords***: *laser, soap film, polariton, soliton, dielectrophoresis.*

Visible and IR laser beams irradiating usual plane or curved soap films of thickness from 10 nm to 10 μm prepared from any soap solution behave in a strange way [1 – 4]. They form narrow (down to submicrons) bright channels propagating in films sometimes over distances of tens of centimetres without the characteristic diffraction-limited divergence and without any noticeably decrease in the intensity. These light tracks (whiskers) change permanently (tens times per second) their direction, abruptly breaking and branching as lightning streamers, and readily cross with each other. Their narrow width is virtually independent of the laser wavelength and laser radiation intensity, which was varied by nine orders of magnitude: from 10 μW up to 2 W in the cw regime and up to 10 kW in a single 10-ns pulse. The narrowness, permanent branching, and changes in the directions of light channels allows us to treat a film with running whiskers as a real operating model of a powerful self-controlled optical computer controlling the film state and permanently determining the time and site of the next branching or change in the directions of tracks [3].

In the case of the optimal adjustment, approximately 10 % of the pump radiation enters the film. The formation time of tracks, as shown in our paper [3], is less than 10 ns. Whiskers are distinctly observed in the film irradiated by 532-nm, 10-ns, 0.2-mJ pulses of green light. The wavelength of light emerging from tracks coincides with the wavelength of the exciting laser with an accuracy of 0.001 nm (experiments were performed using a Fabry – Perot interferometer with the 3-cm base). Similar whiskers were formed in films exposed to short 70-fs laser pulses at 475 and 950 nm with a pulse repetition rate of 85 MHz and an average power of 1 – 150 mW, which demonstrates a high transmission information capacity of self-produced laser channels with such femtosecond light 'bullets'.

By summarising the results obtained, we will attempt to elucidate the mechanism of whisker formation and to understand the reasons for the strange features of their behaviour. Recall these features [1 – 4]:

(1) Whiskers are observed in liquid and dry (see Refs [4, 5]) free soap films of thickness less than 10 μm (experiments were performed using radiation in the spectral range between 440 and 950 nm at radiation powers from 10 μW up to 10 kW).

(2) Whiskers are narrow (5 – 30 μm), their divergence is smaller than the diffraction-limited value, they have sharp ends, perform fast erratic motions on the film, have branches, decompose to new tracks, and can propagate through paths of tens of centimetres.

(3) From 1 to 7 (sometimes more than 20) whiskers emerge simultaneously from the focal spot of the pump and then exist as individual objects.

(4) The refractive index for whiskers in the film (1 – 1.28) is smaller than the refractive index of the bulk solution and can be different for different whiskers in the same film.

(5) Whiskers cross with each other without any noticeable interaction.

(6) Whiskers coming from the film to the air or solution exhibit a normal divergence.

(7) Whiskers change their direction near large particles of dust on the film; small particles of dust have no effect on whiskers. The visible width of whiskers is almost independent of the laser power and wavelength, the type of soap, temperature, and film thickness.

(8) The wavelength of radiation emerging from whiskers coincides with the exciting laser wavelength with an accuracy of 0.001 nm.

(9) Whiskers, as individual rays, can easily (without any noticeable obstacles) move over the film together with the laser beam and change their direction following the change in the laser beam direction. The formation time of whiskers does not exceed 10 ns.

Many hypotheses have been proposed to explain the behaviour of whiskers. Self-focusing does not seem convincing because the characteristic narrowing of whiskers is observed at rather low radiation powers and is independent of the radiation intensity, which was varied by nine orders of magnitude. The explanation with the help of photonic crystals formed by dynamic hypersonic shells surrounding whiskers is not valid because hypersound rapidly decays at such frequencies.

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**A.V. Startsev, Yu. Yu. Stoilov** P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninskii prosp. 53, 119991 Moscow, Russia; e-mail: stoilov@sci.lebedev.ru; Tel.: (095) 1354649

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A considerable rearrangement of molecules or the film itself in the region of whisker localisation would result in the interaction between the crossing whiskers and the mutual influence of tracks on each other; however, this does not occur. Thermal action is not manifested and does not change the whisker appearance even when absorbers are added to the film. The hypothesis about the existence of new laws of the angular and spatial quantisation of light in thin films is also cannot be accepted because the behaviour of whiskers is often independent of the film thickness, and the direction of their propagation in the film with many regions of different colours does not change [4]. The soliton hypothesis requires high light intensities and the existence of nonlinearities, which we did not observe. No long inhomogeneous waveguide filaments over which light could propagate were observed in films. Some other hypotheses can be listed as well, but all the mechanisms considered so far cannot explain the nonlinear conversion of light to thin whiskers with sharp edges along with low intensities of light used in experiments and linear properties of the medium.

The behaviour of light in thin films was theoretically considered, for example, in Ref. [6], where all the possible types of oscillations in films were analysed. However, the authors [6] did not point out the possibility of formation of narrow streamers in films irradiated by light. At the same time, different refractive indices of a set of whiskers emerging from the same focal region are well described by the different mode structure of laser radiation in the whiskers [4].

Optical distortions in the film, which change the direction of the light flux, also change the direction of the track. Therefore, such films with tracks are promising for the use as sensitive detectors, while the application of electro-optical media and conventional externally controlled (or mode-conversion) optical devices opens us the possibility to change rapidly the direction of narrow whiskers and to develop address-controlled non-interacting waveguides. It is necessary to develop the theory of behaviour of light whisker antennas [4] in thin films, to find the most efficient media, the conditions of their excitation and coupling light out of such devices. Thin films can be also used as amplifying laser media [2, 3], and in this connection it is interesting to estimate the parameters of radiation of a long linear whisker laser of width, for example, as small as the diameter of a molecule, and of a closed laser ring formed by such a whisker. The antenna-track formation of narrow beams [4] is also of interest for oscillatory phenomena of a different physical nature.

The explanation of the behaviour of whiskers based on the known properties of light in thin films [6] and microwave antennas [7–9] gives a number of answers to the questions formulated in Ref. [2] and determines the directions of further theoretical and experimental investigations of various controllable optical antenna–waveguide devices [7, 9] with selectively excited modes and of their use in various devices, including optical computers.

A narrow channel formed in the film can operate as a series-supply light antenna [7–9], but how does it appear in a homogeneous medium? An electromagnetic radiation beam propagating through the channel should diverge at least for four reasons:

(i) A light channel of width 5–30 μm [4] should have the diffraction-limited divergence.

(ii) Light should be scattered in a turbid soap solution.

(iii) The beam energy should be scattered from irregularities of the film surface covered by capillary waves and (along with scattering in solution) making tracks bright when viewed from the side.

(iv) A light beam emerging from the focal point in the homogeneous film should diverge because the exciting laser beam has the aperture cone of the focusing angle of about 0.02.

Each of these reasons is sufficient for the laser track of length 30 cm to diverge at least up to a few fractions of centimeter. However, even in the presence of all the four above factors, a track produced by focused radiation from a 650-nm, 5-mW cw laser pointer incident at the grazing angle on the film surface, which propagates along a complicated multicoil trajectory of total length over 30 cm on the concave liquid film sagged below the horizontal plane (Fig. 1), exhibits no divergence. In a homogeneous two-dimensional film, a narrow waveguide track mode that would not be directed by a dielectric structure simply cannot exist.

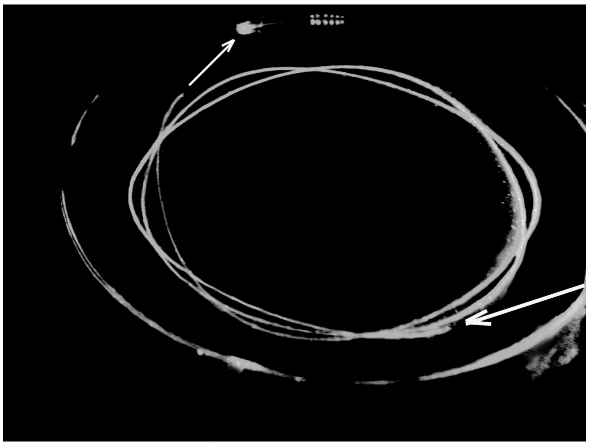

**Figure 1.** Three-coil track of length 35 cm on a concave liquid film of diameter 65 mm. The focal point of a 5-mW cw laser beam on the film surface and the exit of light from the film are shown by the arrows.

Such a behaviour of non-divergent laser tracks is certainly related to the noticeable nonlinear properties of the film, which are especially distinctly manifested in two other specific features:

(1) The formation of whiskers in films irradiated at the grazing angle (according to the classical theory, radiation entering a film at the grazing angle should rapidly leave it after several reflections, without the formation of long tracks experiencing virtually total internal reflection).

(2) The entering of the laser beam to the film and its propagation along chords experiencing total internal reflection (the medium admits light but does not release it) [4] in a thick lower part of the sagged film limited by the ring of a dark film.

The presence of thin light-guiding channels indicates unambiguously that the refractive index $n_1$ of the medium increases in the tracks under the action of low-intensity laser radiation. The increase in $n_2$ can be estimated from the grazing angle ($\sim 5°$) at which the laser beam enters the film. Then, due to the increase in the refractive index from $n_1$ to $n_2$, the beam is captured in the film and propagates over tens of centimetres, experiencing total internal reflection. According to our estimates, $(n_2 - n_1)/n_1 \leqslant 1\,\%$.

For the track width of 30 μm and the difference between the refractive indices equal to 1 %, we obtain (see expression (11.2.14) in Ref. [6]) that about 7 modes can propagate in such a self-produced waveguide channel (even in a thin film of thickness 150 nm). Due to a small ratio $(n_2 - n_1)/n_1$ and different feeding modes, the channels can easily cross with each other, without interaction. They can probably interact with each other only at crossing angles smaller than 1°.

The growth dynamics of a channel (an increase in its length) in the form of a waveguide light antenna from the focal point in the film irradiated by a laser beam is related to a fast stimulated increase in the refractive index of the film near the extreme point of its growth (apex), to which the laser beam arrives through the channel part that has been already formed. The channel disappeared after light was switched off. Thus, light transforms the medium, while the medium collects light. Many variants of such a mutual influence are known [10, 11]. According to our estimates, the specific feature of the mechanism of transformation of the film medium by low-intensity light is that this transformation is related not the laser-field intensity, which was rather low in experiments ($30 - 1000$ V cm$^{-1}$), but to the abrupt field gradients in the film and to dielectrophoresis of molecules in solution.

Dielectrophoresis (the movement of particles in an electric field) appears when an inhomogeneity or gradient is present in a constant or variable electric field. This phenomenon has been already known over 2500 years [12], and it is clearly manifested in the attraction of paper pieces to an electrified rod. The inhomogeneous electric field produces a force that acts on any polarisable objects, both charged and uncharged. Due to the action of the inhomogeneous field on the different ends of a particle and the medium in which the particle is located, particles with the polarisability higher than that of the medium are pulled into the region of a strong field (positive dielectrophoresis), whereas particles with a lower polarisability are ejected into the region of a weaker field (negative dielectrophoresis). The action force is determined by the gradient of the quadratically time-averaged field and is independent of its direction.

The gradients required for the orientation and movement of molecules and particles in solutions due to dielectrophoretic [12 – 15] are produced in our case by laser radiation injected to the film near the 'paling' consisting of the sharp ends of tightly packed soap molecules in two monomolecular surface layers of the film [16]. The rotation, thickening, formation of chains [15], and assembling of molecules in tracks (resulting in the increase in the refractive index) can be used not only to solve the problems of waveguide technology but also for the selective action to separate nanoparticles of different types and molecules in liquid films for applications in nanotechnologies [16]. The change in the refractive index mentioned above will allow one to determine the nature of laser channels. Surface light waves propagating in plane or curved films in the form of narrow non-divergent tracks over distances of tens of centimetres are related to the rearrangement caused by the stimulated variation in the polarisation properties of the medium. Therefore, these waves represent a special combination of the electromagnetic and polarisation energies, i.e., a special type of surface polariton solitons, which were described in Ref. [1] without the detailed discussion of the mechanism of their formation.

The laser tracks observed in the films contain a wealth of information on the structure and composition of the films themselves, and therefore can be used to study them. The studies of tracks and their lasing properties in transformable soap films of different thickness [17] (which have been long studied in detail) are of great interest for physics, chemistry, and biology.

We have explained in Refs [2 – 4] the reasons for the insufficiently rapid development of our studies. For these reasons, our efforts have not yet produced the desirable results, but we hope that our observations will be useful in the future. 'The people pathway' will not be overgrown, and our started project will only increase. We thank our friends for their support and discussions, and for placing solutions for dry films at our disposal. We are also grateful to L.D. Mikheev and V.V. Mislavskii for giving us an opportunity to use a femtosecond laser in our study.

## References

1. Startsev A.V., Stoilov Yu.Yu. Patent Pending No. 20022132754, 5 December, 2002.
2. Startsev A.V., Stoilov Yu.Yu. Preprint FIAN, (2) (Moscow, 2003); http://elphi.lebedev.ru/2/Stoilov.pdf.
3. Startsev A.V., Stoilov Yu.Yu. *Kvantovaya Elektron.*, **33**, 380 (2003) [*Quantum Electron.*, **33**, 380 (2003)].
4. Startsev A.V., Stoilov Yu.Yu. Preprint FIAN, (22) (Moscow, 2003); http://elphi.lebedev.ru/4/Stoilov.pdf.
5. SOAP BUBBLES. http://pubs.acs.org/cen/whatstuff/stuff/8117sci3.html.
6. Yariv A. and Yeh P. *Optical Waves in Crystals: Propagation and Control of Laser Radiation* (New York: Wiley, 1984; Moscow: Mir, 1987).
7. Markov G.T., Sazonov D.M. *Antenny (Antennas)* (Moscow: Energiya, 1975).
8. Budagyan I.F. http://bsfp.media-security.ru/school16/29.htm.
9. Kalashnikov A.M., Stepuk Ya.V. *Kolebatel'nye sistemy* (Oscillatory Systems) (Moscow: Military Publishing House, USSR Defence Ministry, 1972).
10. Chiao R.Y., Garmire. E., Townes C.H. *Phys. Rev. Lett.*, **13**, 479 (1964).
11. Poladian L., Senthilvelan M., Besley J.A., de Sterke M.C. *Phys. Rev. E*, **69**, 016608 (2004).
12. Burke P.J. http://nano.ece.uci.edu/papers/NanoDEPproof.pdf.
13. Zheng L., Li S., Burke P.J., Brody J.P. http://nano.ece.uci.edu/papers/singlemolecule.pdf.
14. Pethig R., Markx G.H. United States Patent 5,814,200; http://164.195.100.11/netahtml/srchnum.html.
15. Hermanson K.D., Lumsdon S.O., Williams J.P., Kaler E.W., Velev O. *Science*, **294**, 1082 (2001); http://crystal.che.ncsu.edu/pdfs/Science-microwires.pdf; http://www.kalergroup.che.udel.edu/index.htm.
16. Stoilov Yu.Yu. Patent Pending No. 2004104449, 17 February, 2004.
17. Stubenrauch C., von Klitzing R. *J. Phys.: Condens. Matter*, **15**, R1197-R1232 (2003).