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Channeling of microwave radiation in a double line containing a plasma filament produced by intense femtosecond laser pulses in air*

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***Abstract*. The channeling of microwave radiation is demonstrated experimentally in a double line in which a plasma filament produced in air by intense femtosecond laser pulses serves as one of the conductors. It is shown that during the propagation of microwave radiation in this line, ultrashort pulses are formed, their duration monotonically decreasing with increasing the propagation length (down to the value comparable with the microwave field period). These effects can be used for diagnostics of plasma in a filament.**

Keywords: *filamentation, Kerr nonlinearity, self-focusing, femtosecond laser pulses.*

1. Introduction

The filamentation of an intense femtosecond laser beam in atmosphere caused by balance between the self-focused Kerr nonlinearity of air and defocusing produced by plasma appearing due to ionisation attracts great attention of researchers [1, 2]. Plasma filaments are used in terahertz radiation sources [3], for triggering high-voltage discharges in megavolt switches, and to control lightnings in storm clouds [4, 5]. A considerable broadening of the laser emission spectrum appearing upon filamentation is also of interest for a number of advanced applications [6].

The channeling of microwave radiation by a plasma filament produced in air by intense femto-second laser pulses is also of current interest. Such channeling can provide the efficient transport of the microwave radiation energy by retaining the high radiation power density over a distance equal to the filamentation length achieving several tens of metres [1]. The use of the plasma produced by nanosecond laser pulses to transport microwave radiation has long been studied [7 – 9]. However, the specific features of application of intense femtosecond laser pulses for microwave radiation channeling in the atmosphere, related first of all to the filamentation of laser beams, attracted the attention of researchers only recently. The authors of theoretical paper [10] proposed to channel micro-wave radiation by using a cylindrical plasma waveguide with walls produced upon multiple filamentation of a femtosecond laser beam. This method was experimentally demonstrated in [11] by using the 100-TW laser facility.

In this paper, we studied experimentally the channeling of microwave radiation in a double line containing a plasma filament as one of the conductors. This idea was discussed earlier in [12]. The single-filament regime used to channel microwave radiation in this case considerably alleviates requirements to the power of femtosecond laser pulses compared to other papers [10, 11].

2. Experimental

We used in experiments the femtosecond Ti : sapphire laser system [13] producing 70-fs pulses at a wavelength of ~ 0.8 μm with a pulse repetition rate of 10 Hz. The maximum laser pulse energy did not exceed 3 mJ. The laser beam of diameter $d \approx 20$ mm (at the $1/e^2$ level) was focused in air by a spherical mirror with the focal length $f = 80.6$ cm. When the pulse energy exceeded the threshold value (~ 0.5 mJ), a luminous plasma filament appeared in the focal region. The filament length achieved 5 cm at the maximal laser pulse energy. The filament served as one of the two conductors of the double line in which microwave radiation propagated. Another conductor of the double line was a copper wire of diameter 0.5 mm.

Microwave radiation of power 1 – 2 mW at frequency 34 GHz from a G4-156 oscillator was coupled into a standard waveguide of size 7.2×3.4 mm (Fig. 1). To match the standard waveguide with the double line [14], the waveguide

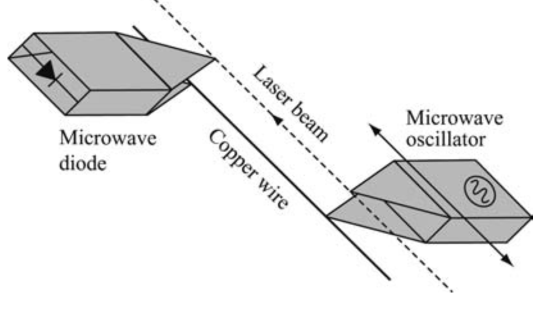

Figure 1. Scheme of the experiment.

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section was symmetrically ground down along the wide wall to zero. A similar ground down waveguide section was used to match the output of the double line with a microwave detector. The length of the double line could be varied by moving the waveguide section with the microwave detector along the conductors. The plasma filament was formed with the help of dielectric mirrors parallel to the copper wire of the double line and was located at distances ~ 100 μm from the tip of the ground down waveguide sections.

A signal transmitted through the double line was detected with the microwave detector connected with a 500-MHz Tektronix TDS-3052B oscilloscope. The plasma filament produced in the focal region during the propagation of a laser pulse led to the formation of the double line in which microwave radiation could propagate. We measured the amplitude and duration of the transmitted microwave pulse as functions of the distance between two sections of the waveguide.

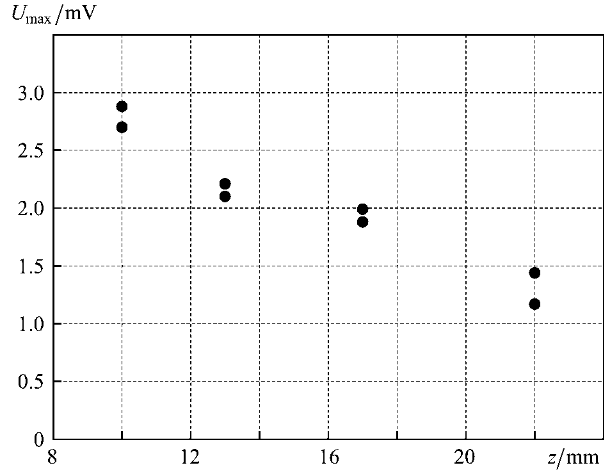

Figure 3. Dependence of the microwave pulse amplitude U_{max} on the length of the double line.

3. Results and discussion

Figure 2 presents the output signals of a microwave diode for a double line of length $z = 2.2$ cm. The dashed curve was obtained in the absence of a femtosecond laser pulse and, hence, in the absence of a plasma filament. A cw microwave signal in this case was determined by the propagation of radiation from the oscillator through the system in the presence of only one (copper) wire in the double line. When a plasma filament was produced by a femtosecond laser pulse, a positive pulse (solid curve) was observed in the oscillogram from the microwave diode, which indicated that the propagation coefficient of microwave radiation increased. This pulse was synchronised with the laser pulse. The microwave pulse duration was approximately 1.5 ns in all experiments and was independent of the double line length and laser pulse energy. It seems that the microwave pulse duration was determined by the time response (instrumental function) of the detection system (microwave diode and oscilloscope) and considerably exceeded the microwave pulse duration at the double line output.

When the microwave oscillator was switched off, but in the presence of the filament, no signal was observed in the oscilloscope. This fact confirms that the microwave pulse transmitted through the double line is due to formation of the filament.

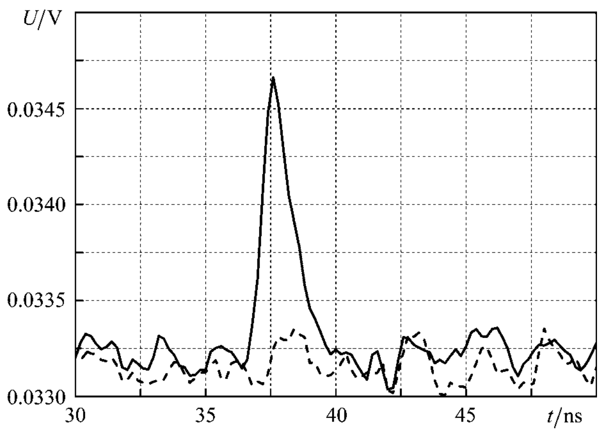

Figure 2. Output signal U of the microwave diode in the presence of a filament (solid curve) and its absence (dashed curve). The length of the double line is $z = 2.2$ cm.

Figure 3 shows the dependence of the amplitude of a pulse microwave signal on the double line length. One can see that the amplitude linearly decreases with increasing the distance between the receiving and transmitting waveguide sections.

Let us discuss now the features of the transport of microwave radiation in a double line in which one of the conductors is a plasma filament. For this purpose, it is convenient to use telegraph equations, which well describe electromagnetic fields in the double line. We will assume for simplicity that the electron concentration distribution n_e along the filament is constant.

According to the theory of transmission lines [14], the dispersion relation between the propagation constant $h = h' - ih''$ for monochromatic waves ($\sim \exp[i(\omega t - hx)]$) and the signal frequency ω has the form

$$h^2 = \omega^2 CL\left(1 + \frac{R}{i\omega L}\right), \tag{1}$$

where $R = 4/(\pi d_1^2 e\mu n_e)$ is the linear resistance of the double line, which is determined by the plasma filament parameters; d_1 is the filament diameter; e is the elementary charge; μ is the electron mobility in air;

$$L \approx \frac{\mu_0}{2\pi}\ln\frac{4a^2}{d_1 d_2},\ C \approx 2\pi\varepsilon_0 \Big/ \ln\frac{4a^2}{d_1 d_2}$$

is the linear inductance and capacity of the line; ε_0 and μ_0 are the permittivity and permeability of vacuum; a is the distance between the conductors of the line; and d_2 is the second conductor diameter.

For $R < \omega L$, it follows directly from (1) that the spatial decay decrement h'' is inversely proportional to the electron concentration in the plasma filament:

$$h'' \approx \frac{R}{2}\sqrt{\frac{C}{L}} \approx \frac{k}{n_e}, \tag{2}$$

where

$$k = \frac{2}{d_1^2 e\mu \ln(2a/\sqrt{d_1 d_2})}\sqrt{\frac{\varepsilon_0}{\mu_0}} = \frac{1}{Z\pi d_1^2 e\mu \ln(2a/\sqrt{d_1 d_2})} \quad (3)$$

is the proportionality coefficient and $Z = 60$ Ohm. The plasma dynamics immediately after the end of the laser pulse producing the plasma is determined by recombination [1], and the concentration n_e after the ionising laser pulse changes by the law

$$n_e = \frac{n_{e0}}{1 + n_{e0}\alpha_r t}, \quad (4)$$

where n_{e0} is the initial free electron concentration (at the laser pulse end); t is time; and α_r is the recombination coefficient.

By substituting (4) into (2), we obtain the expression

$$h'' = \frac{k}{n_{e0}}(1 + n_{e0}\alpha_r t) \quad (5)$$

describing the time evolution of the decay decrement. Here, the time t is measured from the laser pulse.

Taking (5) into account, the microwave signal intensity $I(z,t)$ at the output from the double line of length z is described by the expression

$$I(z,t) = I_0 \exp(-2h''z) = I_0 \exp\left(-2z\frac{k}{n_{e0}}\right)\exp(-zk\alpha_r t), \quad (6)$$

where I_0 is the microwave field intensity at the input to the double line.

As follows from (6), because of the plasma decay, the waveform of microwave radiation in the double line depends on time. As a result, a pulsed microwave signal is formed whose duration is determined by the decay time of plasma and the distance between the receiving and transmitting waveguide sections. The characteristic duration t_{mcw} of the microwave pulse transmitted through the double line proves to be inversely proportional to the line length z:

$$t_{mcw} = \frac{1}{zk\alpha_r}. \quad (7)$$

Let us estimate the microwave pulse duration under our experimental conditions by using the following parameters: the filament diameter $d_1 = 100$ μm [1], the copper wire diameter $d_2 = 0.5$ mm, the distance between the conductors in the double line $a \approx 4$ mm, the electron mobility in a weak field $\mu = 15\,000$ V^{-1} s^{-1} cm^2 [15], the recombination coefficient $\alpha_r = 2 \times 10^{-7}$ cm^3 s^{-1} [16], and the maximal length of the line $z_{max} \approx 2.2$ cm. As a result, we find $t_{mcw} \approx 400$ ps. Such a small value of t_{mcw} confirms the assumption proposed above that the temporal shape of the detected microwave signal is completely determined by the instrumental function of the detector. In this case, we can assume that the maximum amplitude U_{max} of the output signal of the microwave detector is proportional to the microwave pulse energy, i.e. to the time integral from the microwave radiation intensity [17]:

$$U_{max}(z) \sim \int_0^\infty I(z,t)\,dt = \frac{I_0}{zk\alpha_r}\exp\left(-2z\frac{k}{n_{e0}}\right). \quad (8)$$

According to (8), the detected signal is inversely proportional to the length z of the line and directly proportional to the exponential factor, which also contains z. In experiments (Fig. 3), the inversely proportional dependence on the length of the line was observed. This means that the exponential factor does not play any role in the range of measured values, i.e. $2z(k/n_{e0}) \ll 1$. This relation allows us to estimate the plasma concentration in the filament as $n_{e0} > 3 \times 10^{16}$ cm^{-3}. This estimate does not contradict to the known experimental results (see, for example, [1]).

By returning to expression (6), note that because of the high initial plasma concentration in the filament, the amplitude of the microwave pulse propagating in the double line containing the filament remains constant, but the pulse duration decreases inversely proportional to z. As a result, ultrashort microwave pulses are formed at the output of the line, and parameters of these pulses can be controlled by varying the length of the line. The pulse duration estimated above ($t_{mcw} \approx 400$ ps for $z = 2.2$ cm) corresponds only to 14 microwave field periods. By increasing the filament length up to 30 cm, an extremely short microwave pulse duration of about one field period can be obtained.

Thus, we have demonstrated experimentally the channeling of microwave radiation in a double line in which one of the conductors is a plasma filament produced in air by intense femtosecond laser pulses. We have shown that during the propagation of microwave radiation in such a line, pulses are formed with duration that monotonically decreases down to the value comparable with the microwave field period with increasing the length of the double line. By measuring the parameters of these microwave pulses, the diagnostics of the plasma concentration in the filament can be performed.

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