Microwave Propagation via Laser Plasma Channels

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We propose a forward-looking ground penetrating radar using laser produced-plasma channels. The plasma channels work as a microwave guide to and from the buried objects. In order to confirm this method's feasibility, we investigated the propagation properties of plasma channels.

Keywords: forward-looking ground penetrating radar, sensor technology, laser plasma channel, microwave waveguide, propagation gain

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Ground penetrating radar (GPR) is a sensor technology commonly used to investigate underground objects, for example, ruins, cavities under the road, and landmines. It utilizes microwave echoes reflected by the buried objects. Normally, conventional GPR has limited use since it suffers deterioration of resolution and a decrease in back scattering the farther the survey area is located from the GPR's antenna. On the other hand, researchers have started to study forward-looking GPR (FLGPR), which has a potential to detect the objects from a long distance [1]. In order to develop FLGPR, we propose a new detection method using laser plasma channels. The governing principal of this device is to create a guide for the microwave using the plasma channels to reach the survey area. This method may achieve superior resolution, since we can change the wide-angle pattern of microwave radiation to straight-line. Additionally, this has possibilities to enhance the backscatter by the direct coupling of the plasma channels and the buried objects. Moreover, we can expect a further effect of oppressing interference with other communication apparatuses. In this text, as a first step, we selected a pair of parallel lines of plasma as the simplest structure of the plasma waveguide, and investigated its property of microwave propagation.

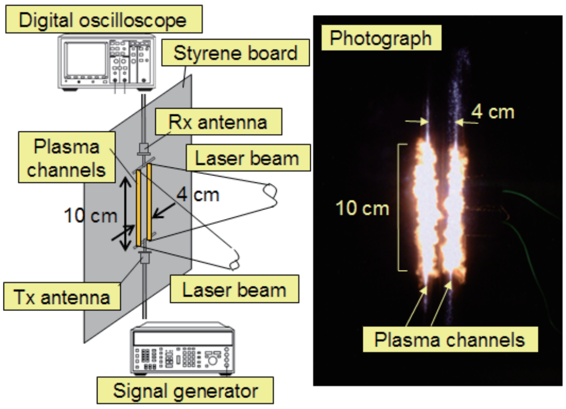

Fig. 1 Experimental configuration. A 10 cm long plasma waveguide was created between the transmitter and the receiver using a pulse laser.

As shown Fig. 1, orthogonal plasma channels were generated along a line-focused laser light and onto a styrene board. This setup created homogeneous and high-density plasma channels when even using a weak laser. The microwave's frequencies tested were 300, 600, and 900 MHz, because they are used commonly in conventional GPR. The transmitter and receiver were fixed onto the back of the styrene board at 10 cm intervals. We intentionally used mismatched antennas 1.3 GHz, to clarify the effect of the plasma channels on wave propagation. A high power laser (wavelength 1, 064 nm, pulse width 10 ns, energy 19 J/pulse) was focused on two parallel lines 10 cm long, 0.1 mm wide, and 4 cm apart. The laser intensity on the styrene board was 1.9×10^{10} W/cm^2.

We first examined the characteristic of the generated plasma channels. We performed laser-induced breakdown spectroscopy and observed the Stark broadening of about 4.5 nm at an Hα spectral line. The maximum electron density n_e was estimated to be 10^{18} cm^{-3} [2], using

$$n_{\mathrm{e}} = C(\Delta\lambda_{1/2})^{3/2}\ [\mathrm{cm}^{-3}], \tag{1}$$

where $\Delta\lambda_{1/2}$ is the length of the Stark broadening [nm] and C is the constant $\simeq 10^{17}$.

We also estimated the average electron temperature T_e as approximately 1.4 eV using the following expression and the measured intensities of the OI spectral lines

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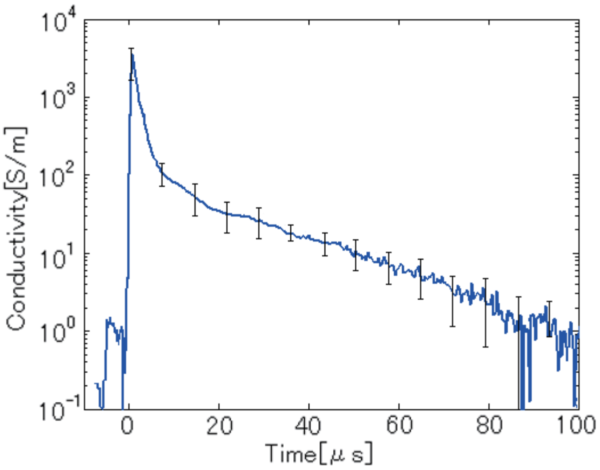

Fig. 2 The evolution of the plasma channel's conductivity. The channels were generated at 0 s. The maximum conductivity was approximately 3,500 S/m, and the decay time was approximately 2 µs.

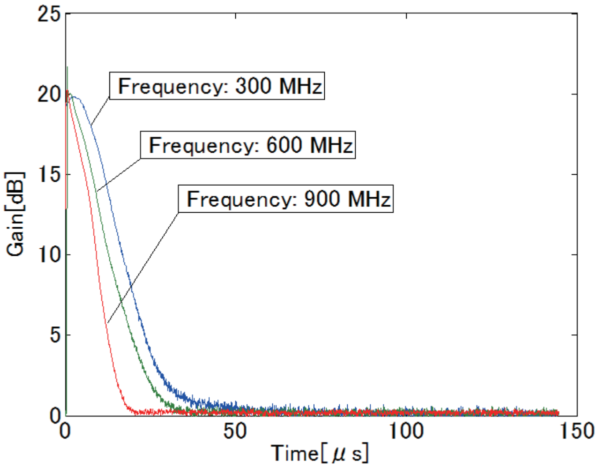

Fig. 3 The evolution of propagation gain. The gain increased to over 20 dB spontaneously and decayed exponentially. Their decay times were over 10 µs.

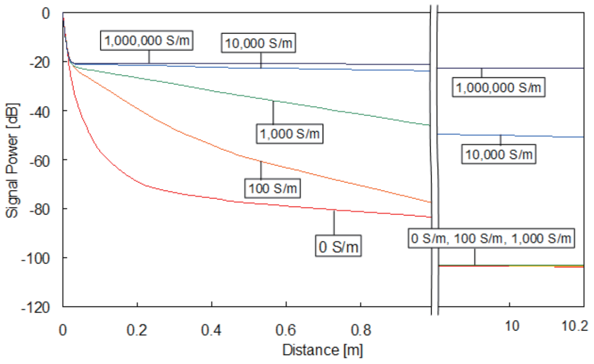

Fig. 4 The relation between the plasma channel's conductivity and the span attenuation of the guided microwave. A high conductivity (over 10,000 S/m) would be desirable in practical use at 10 m.

(716, 777, 795 nm) as follows:

$$T_e = \frac{\epsilon_n - \epsilon_m}{\ln(A_n g_n \lambda_m I_m / A_m g_m \lambda_n I_n)} \text{ [eV]}, \tag{2}$$

where ϵ_n, λ_n, I_n, g_n, and A_n indicate the nth energy level [eV], the spectral wave length [nm], the spectral intensity from the nth level [a.u.], the statistical weight of the nth level, and the atomic transition probability [sec^{-1}], respectively [3, 4].

Figure 2 shows the evolution of the plasma channel's conductivity measured using Langmuir probes [5, 6]. The plasma channels were generated at $t = 0$ s. The maximum conductivity was approximately 3, 500 S(Siemens)/m, and the decay time constant was approximately 2 µs.

Next, Fig. 3 shows the evolution of the propagation gain produced by the plasma channels, which is the ratio of the received power involving the plasma channels divided by that without them. After generating the plasma channels at $t = 0$ s, the gain increased to over 20 dB spontaneously. Afterwards, it decayed exponentially, and the propagation gain's decay time constants were about 20 µs (300 MHz), 16 µs (600 MHz), and 11 µs (900 MHz), respectively. The difference from the mean value was within 3 % during 3 measurements under the same experimental configuration. This clearly shows that a microwave propagated via the plasma channels and that a microwave of lower frequency can propagate for a longer time.

In this experiment, the length of the plasma waveguide was only 10 cm, though for future radar a longer waveguide is necessary. We estimated how much plasma conductivity we need for a 10 m plasma waveguide. Figure 4 shows the relation between the plasma channel's conductivity and the span attenuation of the guided microwave, calculated by an electromagnetic field simulator substituting conductive rods for plasma channels. The curve of 0 S/m indicates the span attenuation without the plasma waveguide. Higher conductivity (100, 1,000, . . . 1,000,000 S/m) results in smaller attenuation rates. At a distance of 10 m, however, the signal attenuation level via the plasma channels of 100 and 1,000 S/m becomes the same as that without the plasma channels. We can conclude that a high conductivity (over 10,000 S/m) would be desirable in practical use at a position 10 m away.

Much stronger laser power is necessary to obtain a 10 m long plasma channel in air, even though a highly conductive plasma with 10,000 S/m may be available around the focal point without a styrene board. Various methods should be utilized to reduce laser power for plasma production. The transmission of lower-frequency microwaves leads to a reduction of the required plasma's conductivity. Utilization of the noise component of a microwave emitted from a locally-produced plasma channel near the ground surface is also a possible candidate. The non-uniformity of a laser-produced plasma causes undesirable microwave reflection and results in a loss of microwave transmission gain. In our experiments, some discrepancies between the measured and the calculated gains can be observed in Fig. 3 and Fig. 4. This might be improved considerably if a continuous plasma channel is generated using an excimer or femtosecond laser pulse ahead of the main laser shot.

In spite of these disadvantages, the method of producing a microwave transmission line through the use of laser power is attractive. Further experimental studies are necessary to solve these problems and to clarify this method's feasibility.

[1] M. Bradley, T. Witten, M. Duncan and B. McCummins, Proc. SPIE **5415**, 421 (2004).
[2] H.R. Greim, *Plasma Spectroscopy* (McGraw-Hill, New York, 1964).
[3] M. Yamamoto and S. Murayama, *Plasma no bunko-keisoku* (The Spectroscopical society, Tokyo, 1995) [*in Japanese*].
[4] W.L. Wiese, M.W. Smith and B.M. Glennon, *Atomic Transition Probabilities. Volume I Hydrogen Through Neon* (National Bureau of Standards, Washington, 1966).
[5] JSPF, *Plasma shindan no kiso to ouyo* (Corona Publishing CO., LTD, Tokyo, 2006) p.21 [*in Japanese*].
[6] H. Sugai, *Plasma Electronics* (Ohmsha, Ltd., Toyko, 2000) p.58 [*in Japanese*].