Ground penetrating radar using a microwave radiated from laser-induced plasma

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Abstract. A plasma column radiates a microwave to surroundings when generated with laser irradiation. Using such a microwave, we are able to survey underground objects and architectures from a remote place. In this paper, the microwave radiated from a plasma column induced by an intense laser (∼10⁹ W/cm²) were measured. Additionally, a proof test of this method was performed by searching an underground aluminum disk (26 cm in diameter, 1 cm in depth, and 1 m apart from a receiving antenna). As the result, the characteristics of the radiated microwave were clarified, and strong echoes corresponding to the edges of an aluminum disk were found. Based on these results, the feasibility of a ground penetrating radar was verified.

1. Introduction
A ground penetrating radar (GPR) is a non-destructive sensor technology commonly used to investigate underground objects or structures of buildings. However, there is a drawback that we must use it nearby the detection area. Therefore, when we survey dangerous areas like tumbledown buildings, nuclear reactors, and minefields, we need to prepare for the hard situation. To solve this drawback, researchers have started to study a forward-looking GPR, which can survey the underground objects from a long distance [1]. One of the technical problems to achieve a forward-looking GPR is how to maintain a good spatial resolution. We propose a new detection method using the microwave radiated from laser-induced plasma as a Laser-driven GPR (LGPR) to resolve this problem.

2. Characteristics of a microwave radiated from laser-induced plasma
The microwave radiated from laser-induced plasma is attenuated by Debye screening. However, a line-shaped plasma can radiate a microwave via surface wave mode [2, 3]. The radiation of a millimeter wave and a THz electromagnetic wave from laser-induced plasma has been demonstrated by N.Yugami et al [4]. In this section, characteristics of a radiated microwave were studied to design a LGPR.

2.1. Common configuration
Figure 1 shows the configuration of our experiments. A Nd:YAG laser (wavelength 1.064 nm, pulse width 10 ns, and pulse energy 40 J) was focused on a line (length 5~30 cm and width 1.5
mm) on a styrene board. A maximum electron density was estimated \( \sim 10^{19} \text{ cm}^{-3} \) by the Stark broadening of H\( \alpha \) (656.3 nm) and a maximum electron temperature was estimated \( \sim 0.11 \text{ eV} \) by Boltzmann plots of Ca II line spectrum (393, 397, and 422 nm). WiNRADiO AX-31B (Log-periodic dipole antenna, frequency range 230 MHz\( \sim \)1600 MHz, linear polarization, forward gain 6 dBi, amplifier gain 20 dB) and Tektronix DPO4104 (frequency range up to 1 GHz, sampling rate 5 Gs/s) were used as a receiving antenna and a waveform recorder respectively.

![Figure 1. Setup of the experiments. An intense laser line-focused on a styrene board at atmospheric pressure. The length of a plasma column was variable from 5 cm to 30 cm by an aperture. An electron density and temperature were estimated to be \( \sim 10^{19} \text{ cm}^{-3} \) and \( \sim 0.11 \text{ eV} \) respectively.](image)

### 2.2. Spectrum

Because a dumping of propagation in soil and a radar cross section of a scattering object depends on microwave’s frequency, a radiated spectrum is very important for a LGPR.

The receiving antenna was settled 80 cm away from the plasma column. The direction of polarization of the receiving antenna was parallel to the plasma column. The length of a plasma column was varied 7, 8, 10, 13, and 20 cm using apertures. The laser intensity was kept constant at \( \sim 10^9 \text{ W/cm}^2 \). A pulse width was also kept constant at \( \sim 10 \text{ ns} \) (FWHM) independently of the plasma length. However, both peak frequency and peak intensity were shifted as the plasma length changed. These results indicate that the peak frequency is controllable by the plasma length. Figure 2 shows the peak frequency and the peak intensity as a function of the plasma length. When the radiated spectrum is assumed as a product of the shape-depended and the plasma-depended spectrum, the peak frequency \( f_{\text{peak}} \) and the peak intensity \( I_{\text{peak}} \) are shown with following expressions,

\[
\begin{align*}
  f_{\text{peak}} &= \frac{\sigma_{\text{shape}}^2 f_{\text{shape, peak}}^2 + \sigma_{\text{plasma}}^2 f_{\text{plasma, peak}}^2}{\sigma_{\text{shape}}^2 + \sigma_{\text{plasma}}^2}, \\
  I_{\text{peak}} &= \frac{1}{2\pi\sigma_{\text{shape}}\sigma_{\text{plasma}}} \exp\left(-\frac{(f_{\text{shape, peak}} - f_{\text{plasma, peak}})^2}{\sigma_{\text{shape}}^2 + \sigma_{\text{plasma}}^2}\right),
\end{align*}
\]

where \( f_{\text{peak}}^\text{shape}, f_{\text{peak}}^\text{plasma}, \sigma_{\text{shape}}, \) and \( \sigma_{\text{plasma}} \) are the peak frequency of shape-depended spectrum, the peak frequency of plasma-depended spectrum, the standard deviation of shape-depended spectrum, and a standard deviation of plasma-depended spectrum respectively. The shape- and the plasma-depended spectrum were assumed as a normal distribution \( N(f_{\text{peak}}, \sigma) \). \( f_{\text{shape}}^\text{shape} \) was given as the resonance frequency \( C/(2 \times l_{\text{plasma}}) \), where \( C \) is the speed of light and \( l_{\text{plasma}} \) is the plasma length. On the other hand, \( f_{\text{peak}}^\text{plasma} \) was taken to be a constant in this experiment. As the result of fitting to measured data, \( \sigma_{\text{shape}}, \sigma_{\text{plasma}}, \) and \( I_{\text{peak}}^\text{plasma} \) were estimated as 0.90 GHz, 0.37 GHz, and 0.50 GHz respectively.
2.3. Radiated power

For an estimation of a laser power needed for a LGPR, it is necessary to clarify the power ratio of an output microwave power to an input laser energy fluence.

A receiving antenna settled 80 cm away from a plasma column. A plasma length was fixed to be 25 cm. The laser energy fluence was varied from 7 to 12 J/cm². Measured data were calibrated with a signal generator and the reference antenna identical to the receiving antenna to acquiring the absolute value.

Figure 3 shows the relation between the radiated power and the laser energy fluence. The radiated power has increased in proportion to the laser energy fluence. When the laser energy fluence fell below $\sim 7.5$ J/cm², the laser-induced plasma was not generated.

3. Proof test

Figure 4 shows the configuration of a proof test to verify the feasibility of our method. An aluminum disk (26 cm in diameter) was buried at 1 cm depth in a sand layer ($\epsilon_r = 5, \sigma = 10^{-5}$ S/m) within a polypropylene tray (1.2 m x 0.8 m) 0.9 m away from a receiving antenna. Microwaves from laser-induced plasma were measured while moving focal points little by little as shown in Figure 5.

Figure 6 shows a measured data after a signal processing as XY-contour images of a sand box. Strong echoes from the edges of an underground aluminum disk were found. However, the signal hardly returned from a center of an aluminum disk. This is because the phase of the propagating microwave is inverted by a reflection on a metal, resulting in that the direct and the reflected wave cancel each other. This phenomenon might be troublesome to investigate a survey area. To avoid this problem, it may be effective to increase the measurement density and clarify the edge of objects.
4. Conclusion

In this paper, the basic characteristics of a microwaves radiated from laser-induced plasmas were clarified experimentally. The feasibility of proposed LGPR was verified by detecting an underground aluminum disk. For the improvement of the detection performance, more fine increment of the measurement density is desirable.

References

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