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Dynamic dipole polarizability of gold and copper atoms for 532- and 1064-nm wavelengths

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The fast electrical explosion of fine metal wires in a vacuum will produce calibrated gas cylinders of metal atoms surrounded by a low-density corona. For fully vaporized wires, the integrated-phase technique, based on laser interferometry, provides the dynamic dipole polarizability of metal atoms. A fast-rising current of $\sim$1 kA/ns will vaporize thin 12.7-μm-diameter Au and Cu wires in a vacuum and generate a radial-expanding gas cylinder surrounded by low-density plasma corona. Employing the integrated-phase technique on fast-exploding Au and Cu wires, we find that the dynamic dipole polarizability of Au atoms is $8.3 \pm 0.8\,\text{Å}^3$ for 532 nm and $7.0 \pm 0.7\,\text{Å}^3$ for 1064 nm. Measurements collected from exploding Cu wire provide dynamic dipole polarizability of $10.2 \pm 1\,\text{Å}^3$ for 532 nm and $6.5 \pm 0.7\,\text{Å}^3$ for 1064 nm. All experimental values correspond to theoretical predictions based on quantum-mechanical calculations.

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I. INTRODUCTION

Dipole polarizability is one of the fundamental atomic properties and is required to obtain important atomic characteristics such as oscillator strengths, induced dipole moments, dielectric constant and refractive index, Stark and Kerr effects, van der Waals constants, and other characteristics related to the interaction of atoms with external electric fields [1–3]. Experimental data showing dynamic and static polarizability measurements for metal atoms are very limited, and what can be found in the literature are mainly based on theoretical calculations [1–4]. There is a lack of experimental data for dipole polarizability for metal atoms in the literature [3].

The main problem for measurements of atomic polarizability of metals is the creation of a predictable volume of metal gas. This problem can be resolved by a fast electrical explosion of thin metal wire in a vacuum [5–8]. Hu and Kusse [5] propose the use of exploding wires with simultaneous interferometry and x-ray probing for measurement of dynamic polarizability of Ag atoms. This technique is quite sophisticated and requires an additional high-current pulser for driving of the X-pinch synchronized with a short-pulse probing laser. The analysis relies on the axial symmetry of the expanding wire. To generate a proper x-ray probing pulse, they used an XP pulser with 100-ns pulse width and 450-kA peak current [5]. Thin wire was exploded by a separate low-current pulser LC1 with 300-ns pulse width and 4.5-kA peak current [5]. This technique gives the reasonable value of Ag atomic polarizability of $\sim$12 A^3 for 532-nm wavelength. The deposited energy required to turn Ag wire with a dielectric coating to the gas state was 2.7 times higher than atomization enthalpy. Unfortunately, this is the only publication [5] in the literature due to the technical complexity of the proposed technique.

Sarkisov *et al.* [6] proposed the integrated-phase (IPh) technique to measure the dynamic dipole polarizability of Ag, Au, Al, Mg, and Cu metal atoms. This technique is based only on interferometry of the exploding wire in a vacuum and does not require axial symmetry of the expanding wire. For a fully vaporized metal wire, the radial phase-shift integral will reach a maximum value and is proportional to the initial linear density of atoms. The partially vaporized wire will produce a smaller value of the radial phase-shift integral. For a wire core in the partially ionized state, the radial phase shift will be smaller than that of a gas state. To get the true value of dynamic atomic polarizability it is necessary to find the maximum of the radial integral from the interference phase shift versus expansion velocity and the deposited energy [6].

The IPh technique was used to determine dynamic polarizability of W atoms at 532 nm [7]. Experiments were done with a fast-rising current of $\sim$1 kA/ns and thin W wire of $\sim$12-μm diameter with a dielectric coating. Similar results were demonstrated for dielectric coated W wire by Shi *et al.* [8] using the same IPh technique.

In our paper, we present measurements of dynamic atomic polarizability for Au and Cu atoms at two wavelengths, 532 and 1064 nm, using fast exploding fine metal wires in a vacuum and the IPh technique [6].

II. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The experimental setup is based on a fast 80-kV solid-state pulser FPG-80-01NM (FID GmbH, 5-ns rise time, 80 kV on a 50-Ω load, 7-J energy, 40-ns duration time, 1-ns jitter). The coaxial target unit and vacuum chamber are presented in Fig. 1. The vacuum chamber has four 2-in. optical windows for diagnostic. The FID pulser was connected to the coaxial target unit with a high voltage cable. Current and voltage were measured with downstream 1.2-GHz bandwidth coaxial,

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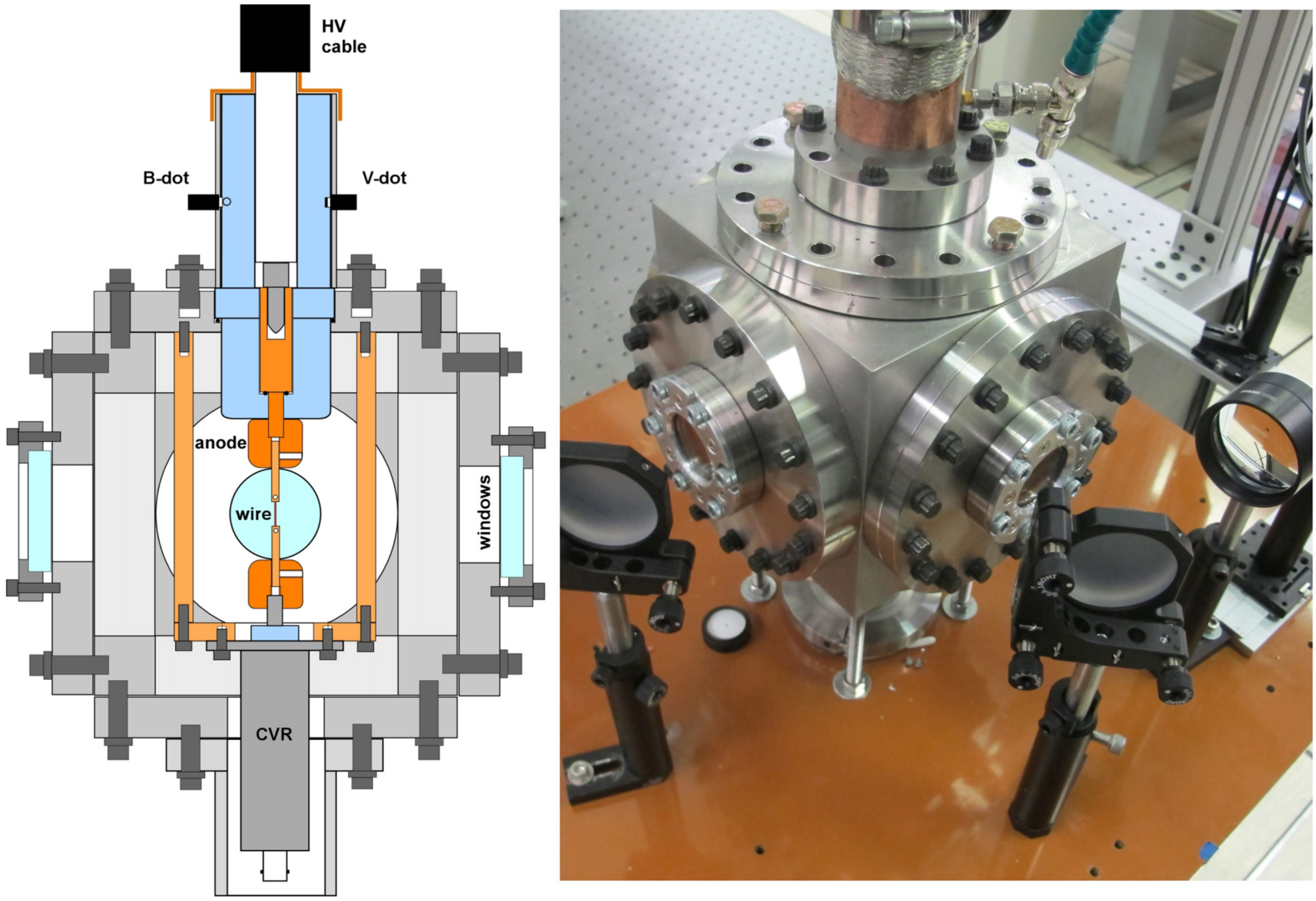

FIG. 1. Vacuum chamber with coax target unit.

0.05-Ω current viewing resistor (CVR, T&M, 1M-T10), and a fast upstream V-dot probe. The vacuum chamber, based on a 6-in. stainless steel cube, can be evacuated up to 10^{-3}-Torr pressure to avoid shunting air breakdown. All waveforms were captured by a Tektronix DPO3054 500-MHz four-channel digital oscilloscope. The Au and Cu wires, 10-mm length and 12.7-μm diameter, are placed in the center of the coaxial target unit inside of the vacuum chamber. The pulser current rate through the wire is ∼1 kA/ns.

Figure 2 shows the optical diagnostics setup. A short-pulse Q-switch Nd:YAG laser (TEMPEST 1-30, 100 mJ at 1064/532 nm, 3-ns pulse width, 1-ns jitter) was used for backlighting the exploding wire. A shearing air-wedge interferometer [9] was utilized to obtain the two-wavelength interferograms on two CCD cameras (FLI ML8300, 12 bit) with appropriate optical filters. To reduce optical aberration the angle plane of the glass wedge was adjusted orthogonally to the beam-splitting plane.

The radial integral of the interference phase shift from a totally vaporized wire is proportional to the linear density of the wire [6]. Expansion velocity of the wire increases with deposited energy. The phase state of the expanding wire core is dependent upon the amount of deposited joule energy before breakdown. For partially vaporized or partially ionized wire, the radial phase-shift integral has a lower value than a totally vaporized wire [6]. The radial integral of the interference phase shift reaches a maximum value when the wire core has fully transformed to a gas state [6]. Our experimental goal is to determine the maximum radial integral of interference phase shift versus expansion velocity in order to reconstruct the dynamic polarizability of the metal atoms. The expression for recovering the average dynamic dipole polarizability $\alpha(\lambda)$ at a wavelength λ can be written as [6]

$$\alpha(\lambda) = \frac{\lambda}{2\pi N_{\text{lin}}} \int \delta(y)dy \tag{1}$$

where α is the atomic polarizability in cubic centimeters, λ is the wavelength in centimeters, N_{lin} is the linear density of atoms in the wire per centimeter, δ is the radial interference

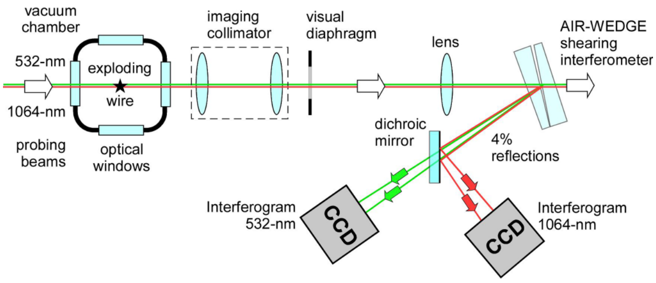

FIG. 2. Optical setup with a two-wavelength interferometer.

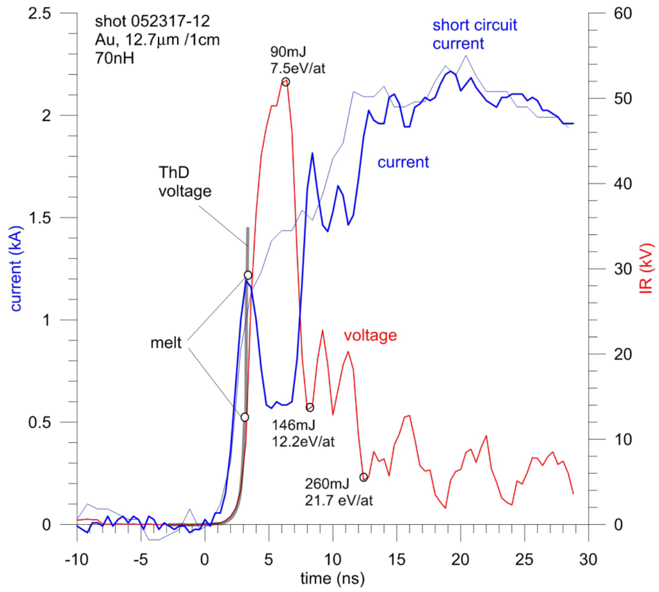

FIG. 3. Current, resistive voltage *IR*, and ThD calculated resistive voltage for exploding Au wire.

phase shift in fringes, and y is the probing path in centimeters in the direction perpendicular to the wire axis. The IPh technique [6] does not require axial symmetry of the expanding wire column. Instead, we assume that the wire expands in the radial direction and the linear density of expanding mass in the radial direction is an invariant value. Probing time is considered to be the initial moment when the expanding wire core becomes transparent to the probing laser. The phase shift from a fast expanding low-density corona is weak and can be neglected in the reconstruction of the radial phase-shift integral.

III. EXPERIMENTAL RESULTS

A. Explosion of Au wire

Figure 3 shows current, voltage, and thermodynamic (ThD) calculated voltage [10] waveforms for an exploding 12.7-μm-diameter Au wire with 1-cm length (shot 052317-12). Resistive voltage *IR* was reconstructed from measured voltage by subtracting the inductive part LdI/dt [11]. The inductance of a wire and the wire's holders was recovered using the first ~40-kV inductive peak which was generated earlier in time by the fast-rising current $dI/dt \sim 1$ kA/ns that equals ~70 nH. A ThD calculation [10] of wire heating demonstrates reasonable agreement with the experimental resistive voltage up to melting time. The current waveform demonstrates resistive behavior up to 12 ns. After 12 ns, the current waveform coincides to the short circuit current due to dropping of the corona resistance to sub-ohm level. According to the ThD calculation, the melting of W wire starts at 13 kV (~3 ns). The amount of deposited joule energy is ~146 mJ (~12.2 eV/atom). This deposited energy corresponds to ~3.3 times the atomization enthalpy for Au (~3.6 eV/atom) and should fully transform the Au wire core into the gas state.

Figure 4 presents two interferograms at 150-ns probing time on a 532-nm wavelength [Fig. 4(a)] and a 1064-nm wavelength [Fig. 4(b)], and recovered complimentary radial phase-shift profiles from cross section A-A [Fig. 4(c)]. The reconstruction error is ±0.05 lines. The linear density of the 12.7-μm Au wire is $\sim 7.47 \times 10^{16}$ atoms/cm. Average atomic density at the moment of probing is $\sim 4.6 \times 10^{18}$ atoms/cm^3. The expansion velocity is ~4.8 km/s. Using Eq. (1), we can reconstruct the dynamic dipole polarizability for 532 nm, $\alpha(532) = 8.3 \pm 0.8$ Å^3, and for 1064 nm, $\alpha(1064) = 7.0 \pm 0.7$ Å^3.

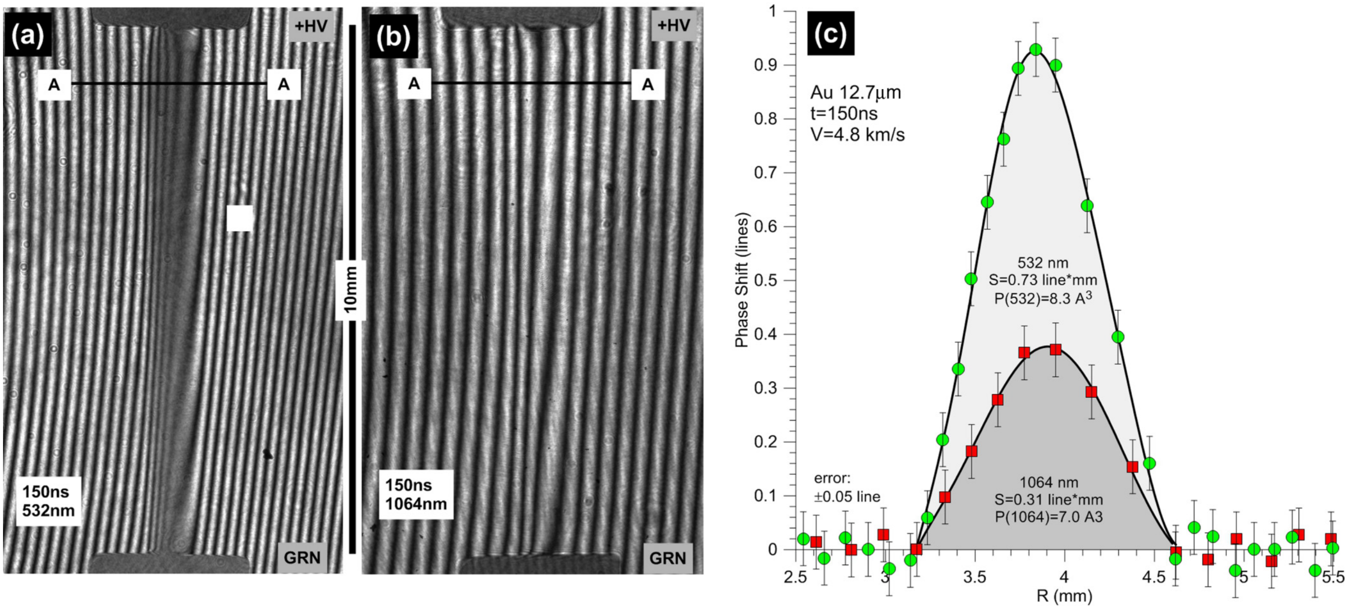

FIG. 4. Interferograms of exploding Au wires at 150 ns for 532 nm (a) and 1064 nm (b), and phase shift (c).

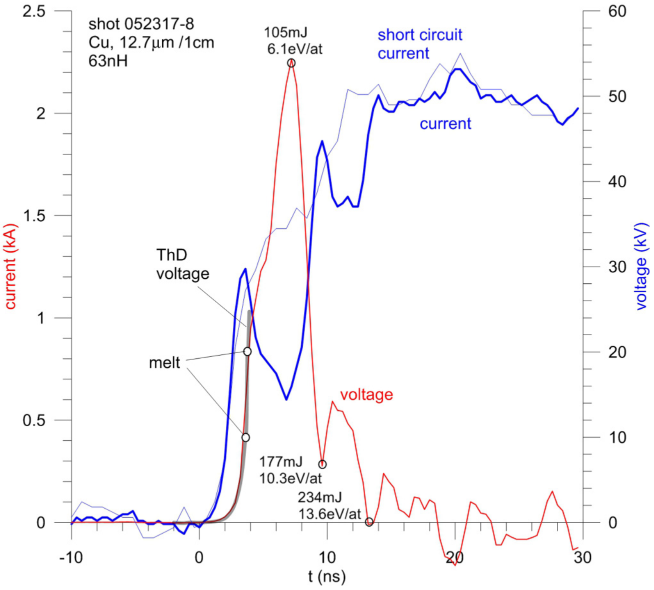

FIG. 5. Current, resistive voltage *IR*, and ThD calculated resistive voltage for exploding Cu wire.

B. Explosion of Cu wire

Figure 5 shows current, resistive voltage *IR*, and ThD calculated resistive voltage waveforms for an exploding 12.7-µm-diameter Cu wire with 1-cm length (shot 052317-8). The inductance of the wire and wire's holders was recovered from the first $\sim$35-kV inductive voltage peak which was generated earlier in time by the fast-rising current and equals $\sim$63 nH. A ThD calculation of wire heating demonstrates good agreement with the experimental resistive voltage up to melting time. The current waveform demonstrates resistive behavior up to 13 ns. After 13 ns, the current waveform coincides with the short circuit current due to the switch of current from a high-resistive core to a fast-expanding plasma corona. According to the ThD calculation, the melting of Cu wire starts at $\sim$10 kV and finishes at $\sim$20 kV. The amount of total deposited joule energy is $\sim$177 mJ ($\sim$10.3 eV/atom). This deposited energy corresponds to $\sim$2.6 times the atomization enthalpy ($\sim$4.0 eV/atom) and should fully transform the Cu wire core into the gas state.

Figure 6 presents two interferograms at 100-ns probing time on a 532-nm wavelength [Fig. 6(a)] and a 1064-nm wavelength [Fig. 6(b)], and the recovered complimentary radial phase shifts from cross section A-A [Fig. 6(c)]. The linear density of the 12.7-μm Cu wire is $\sim 1.1 \times 10^{17}$ atoms/cm. Average atomic density at the moment of probing is $\sim 3.9 \times 10^{18}$ atoms/cm^3. Expansion velocity is $\sim$7.5 km/s. Using Eq. (1), we can reconstruct the dynamic dipole polarizability for 532 nm, $\alpha(532) = 10.2 \pm 1$ Å^3, and for 1064 nm, $\alpha(1064) = 6.5 \pm 0.7$ Å^3.

IV. DISCUSSIONS

We can compare our experimental results with the quantum-mechanical calculation in Ref. [6]. Table I shows calculated and experimental dynamic dipole polarizability for Cu and Au atoms for 532- and 1064-nm wavelengths, deposited specific energy, and expansion velocity in vacuum. The accuracy of the calculations was estimated in Ref. [6] as ±25%, and the experimental error was estimated to be ±10% [6]. We can see that our experimental results match the calculation with accuracy better than 10%. To convert Cu and Au wires to the gas state we spend 2.6 (Cu) and 3.3 (Au) times the atomization enthalpy due to phase transformation under high pressure of magnetic field and shock waves [11]. A similar phase transition, or "overheating," of the substances was demonstrated in Ref. [12] for Al and Cu wires and in Ref. [5] for Ag wire. For Al and Cu wires [12], we have shown overheating of two to three times the tabulated value of atomization enthalpy.

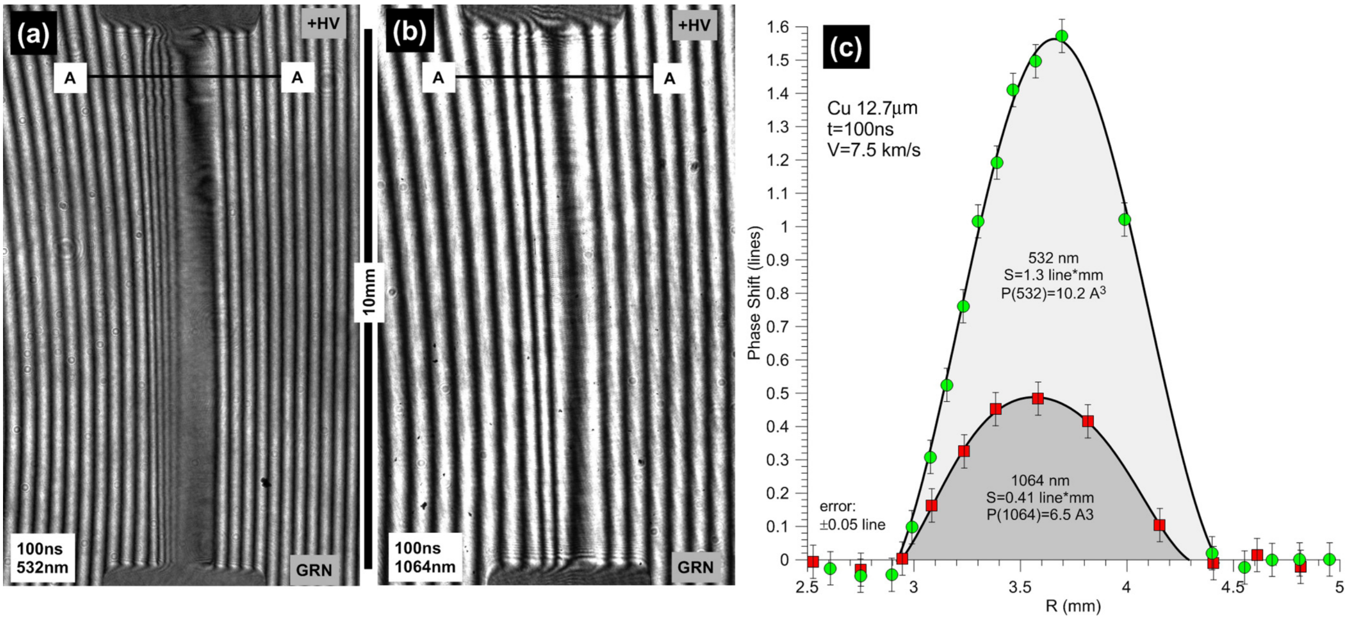

FIG. 6. Interferograms of exploding Cu wires at 100 ns for 532 nm (a) and 1064 nm (b), and phase shift (c).

TABLE I. Calculated and experimental dynamic dipole polarizability for Cu and Au atoms for 532- and 1064-nm wavelengths, deposited energy, and expansion velocity in vacuum.

	Calculation (Å^3, ±25%)		Experiment (Å^3, ±10%)		Deposited energy		Velocity
Atom	α (1064 nm)	α (532 nm)	α (1064 nm)	α (532 nm)	eV/atom	$E_{\text{joule}}/E_{\text{atom}}$	km/s
Cu	6.6	9.3	6.5	10.2	10.3	2.6	7.5
Au	7.3	8.1	7.0	8.3	12.2	3.3	4.8

For Ag wires [5] the metal to gas transformation was done by overheating 2.7 times the tabulated atomization enthalpy value.

By using the integrated-phase technique [6], we extend the set of important atomic physics data about dynamic dipole polarizability for metal atoms. The integrated-phase technique is the only way to get these data virtually for any metals from the Periodic Table of Elements of Mendeleev. The only restriction is the ability to make thin 10–20-μm-diameter wire from these metals.

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