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Observation of photoacoustic Smith-Purcell radiation

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Relativistic electrons moving over a periodic metal grating can lead to an intriguing emission of light, known as Smith-Purcell radiation (SPR), the precursor of the free-electron laser. During the radiation process, the speed of light plays a critical role in determining the emitted angle and frequency spectrum. Inspired by the photonic SPR, here we experimentally demonstrate a photoacoustic version of the Smith-Purcell effect using laser-induced surface shock waves generation. We observe similar acoustic radiation pattern and their associated frequency spectrum in the far-field, perfectly predicted by a universal theory working for both the photonic and acoustic SPR. Moreover, our numerical studies reveal non-constant frequency components due to the supersonic traveling of the shock waves in the near field, greatly contrasting its photonic counterpart. This scheme extends the SPR into the acoustic domain by levitating the wave's speed limit, paves the way towards coherent acoustic wave generation and microstructure metrology.

Smith-Purcell radiation (SPR), a classical type of electromagnetic radiation generated from free electrons moving over a metallic grating[1], allows broadband emission of electromagnetic (EM) waves ranging from terahertz waves, visible light to X-ray[2-4], building up the foundation for the free-electron laser[5,6], which is capable of producing high-intensity coherent and broadband sources as electron micro-bunches travel through designed magnetic undulators in a similar manner[7]. Compared with other relativistic radiation sources such as synchrotron and cyclotron radiation[8,9], SPR-based free-electron light sources are more compact and tunable, given the fact that the wavelength of the emitted light depends on the energy of the electron beam as well as the structure of the periodic surroundings. This offers an opportunity to further shrink the size of these devices with the help of the recent development of nanofabrication technologies, making it even possible to realize on-chip implements of such SPR-based light sources[10-13].

Unlike Cherenkov radiation's occurrence has to overcome a speed limit set by the phase velocity of light in a medium[14-17], SPR is a threshold-less process behaving like a simple Bragg scattering of light when electron wave packages travel near a metallic grating, where a constant light velocity fundamentally defines the angle relations of radiation's wavelength[18-21]. Here the speed of light plays a crucial role for both Cherenkov radiation and SPR, inspiring recent analogous works of nonlinear Cherenkov radiation in nonlinear optics[14,22-24]. It is also interesting to explore other analogous forms of SPR in physical systems[25,26] like acoustics[27], phononics[15,28], exciton-polariton[16], where the wave speed is not limited and affected by many factors such as density, dispersion, pressure. Especially, unlike its counterpart of electromagnetic wave limited by the speed of light, the sound speed barrier can be easily broken in the supersonic regime. Moreover, a sharp shock wavefront can be analogously treated as an ultra-broadband acoustic wave source, exactly imitating the moving free electrons in the case of SPR. This introduces some unique features to this kind of radiation in an acoustical form, and lead to potential acoustical applications in sensing[29] and acoustical sources[30,31].

In this work, we experimentally demonstrate a photoacoustic Smith-Purcell effect using laser-induced surface shock waves, which are sequentially excited in a periodical grating pattern. The resulted acoustic radiations are studied in the far-field and the near-field regimes, where the far-field radiation pattern exhibits an angular dispersion according to a universal angle relationship suitable for both photonic and acoustic SPRs. Similar to its photonic counterpart, the observed photoacoustic SPR also depends on the effective velocity of shock waves. On the other hand, supersonic travel of shock waves dramatically alters the dynamics of SPR in the near field, shrinking the temporal periodicity by breaking the sound speed limit. While these features are only preserved in the near field, having less impact on the far-field radiation. These results introduce the concept of the Smith-Purcell effect into the acoustic wave regime, paving a new way for their practical applications in microstructure sensing and coherent acoustic wave sources.

Fig. 1. Schematic of Smith-Purcell radiation (SPR). (a) the electron bunch moving over the metallic grating with a period D , stimulating angular-dependent broadband electromagnetic (EM) waves. In comparison, (b) shows the schematic of photoacoustic Smith-Purcell radiation. The incoming shock wavefront is scattered periodically by the grating, forming a similar radiation pattern at the far-field. (c) a numerical FDTD simulation based on (a), a bunch of electrons with speed $0.5c$ moving across the metal grating (period 500nm) emits EM waves at the optical frequency. (d) the effective quasi-phase line (dashed, normal to OL_1) depicts the angle dependence in the broadband SPR in (b). By the moment the detector captures the first shock front (blue) from source O , the secondary shock front from source A propagates to the detector. The delay time (Δt) for the detector to catch the later shock wave varies with the detection angle, accordingly the received frequency is also changed.

A classical SPR in the photonics arises from the Bragg type scattering of an electron wave package which is uniformly moving near a metal periodic grating as shown in Fig. 1. The electron can be considered as a single point source in time composed of ultra-broadband electromagnetic waves, which can be scattered into free space by each tooth on the grating. If the grating contains certain periodicity, these scattered waves coherently form EM waves at a particular frequency/wavelength at a particular angle defined by the Bragg condition [19,21] as shown in Fig. 1a, c, where both the velocity of the moving electrons and the periodicity of the grating play a prominent role in this angled emission spectrum. Similarly, if a sharp acoustic wavefront, e.g., shock wave, travels uniformly at a speed of v (non-uniform speed case shall be discussed later) near the top surface of a grating structure with a periodicity of D , each tooth of the grating acts as an individual point emitter, which sequentially scatters the acoustic wave into free

space(Fig. 1b, d). Due to the coherent constructions of wavefronts according to Huygens' principle, a photoacoustic type of SPR in this setup will also spread its frequency-dependent radiation in different angles like its counterpart in the photonic case. If the sound speed is constant, we can obtain the same angle relations as:

$$m\lambda = v_a \cdot \Delta t = D \cdot \left(\frac{v_a}{v} - \cos \theta \right) \quad (m=1) \quad (1)$$

where D denotes the grating constant. v_a is the velocity of the acoustic wave, θ is the emission angle shown in Fig. 1d. This is the exact same formula for the photonic SPR[2-4] according to the same underlying principles.

Fig. 2. Experimental observation of photoacoustic Smith-Purcell Radiation in the far-field. (a) Given a rotating mirror with a stable angular speed ω , the pump is scanned and focused onto the target alumina plate sequentially in the order $a_0 \rightarrow a_1 \rightarrow a_2$, forming an effective laser-induced plasma shock wave array(b). The detector acquires the SPR signals also in the order $b_0 \rightarrow b_1 \rightarrow b_2$. For a fixed detection angle θ and rotating ω , the time delay Δt remains unchanged and irrelevant with the detector's distance in the far-field. (c) is the measured real-time temporal signal and its corresponding spectra(d) with a peak frequency at 10.58kHz. The signal is collected and processed at a surface scanning speed of 10m/s (effective periodicity ~ 1 mm) at $\theta=0^\circ$.

As shown in Fig. 2, a nanosecond laser(~ 10 ns, 200 μ J, 10kHz) is uniformly scanning across a flat metallic surface to induce an array of plasma sparks at its focus. These sparks not only radiate bright visible light emission in Fig. 2b, but also excite localized shock waves sequentially[32]. Note that, the plasma sparks are not ignited at the same time, the time lag between two adjacent spots is determined by the laser repetition rate. To simulate the moving dynamics, a careful mirror scanning speed and the constant repetition rate of the laser ensure equal distances between two adjacent sparks(Fig. 2a), such that the grating period is determined by $D = v/f_{rep}$, where f_{rep} is the repetition rate of the laser, v is the moving velocity of the laser spot. In this manner, we expect the same radiation pattern as proposed in Eq. 1. To observe such photoacoustic SPR, we place a microphone detector on a rotational stage to measure the angular emission pattern. The microphone is connected to an oscilloscope to trace the received temporal

acoustic signals(Fig. 2c) and their corresponding frequency spectra(Fig. 2d). Effectively, this configuration also resembles an acoustic version of a phased array as in the microwave regime[33].

Furthermore, by varying the detection angle θ and the moving velocity v , the effective SPR can be measured in terms of its peak frequency according to Eq. 1. As shown in Fig. 3a-d, for a fixed angle, the detected SPR's frequency increases with the effective moving velocity of laser spots for two detection angles at 0° & 30° , fitting well with the theoretical curve calculated by Eq. 1. Note that, the laser repetition rate is fixed at 10kHz for both cases, the received SPR can even double to twice of the harmonic, ~ 20 kHz, in the forward direction (0°). Meanwhile, a full angle scan (Fig. 3c, d) reveals a declining trend of the SPR's central frequency from the forward direction to the backward one (180°), this also coincides with the theoretical prediction. These results exactly resemble the feature of angle spectrum observed in photonic SPR[2-4], verifying the same physical roots for both cases.

Fig. 3. Angular and velocity dependence of photoacoustic Smith-Purcell Radiation in the far-field. (a) and (b) testify the velocity-dependent frequency with fixed detection angles 0° and 30° respectively. Insert in (a) and (b) are the spectrum collected under the condition with surface velocity 65.7m/s (effective grating period 6.57mm) and 140.1m/s (effective grating period 14.01mm). (c), (d) demonstrate the angular dependence in the photoacoustic SPR specially picked at surface velocity 65.7m/s and 140.1m/s. The dots are experimental measurements and the solid lines are the theoretical curves calculated by Eq. 1.

However, unlike the photonic SPR where the light speed is a constant, the initial velocity of the shock wave in the photoacoustic case can easily exceed the sound barrier, i.e. supersonic, and quickly decay to the normal constant sound speed in a short propagation distance. In fluid dynamics, it has been shown the shock wave propagation can be well described as Sedov-Taylor model[34,35]:

$$R = \alpha \left(\frac{E}{\rho_0} \right)^{\frac{1}{2+\beta}} \cdot t^{\frac{2}{2+\beta}} \quad (2)$$

where R represents shock wave propagation distance from its initial explosion, α is a dimensionless constant

approximately 1, E refers to the energy transferred into shock wave, ρ_0 stands for air density at room temperature, β is the dimension number for propagation, t implies the shock wave propagation time.

Experimentally, we also verify the laser-induced shock wave's propagation using a laser interferometer (Fig. 4a), where a probe (He-Ne laser) in one beam arm is focused near the laser shock wave regime to sense the shock wave induced phase disturbances by interfering with another beam arm. The measured shock wave propagation times are plotted at various distances away from the laser shock wave source, the result well aligns with the theoretical curved predicted by the Sedov-Taylor model in Fig. 4b. The inverse of slope of this distance-time curve reveals the acoustic speed of the shock wave. Obviously, the shock wave's speed is maximized near the laser spot (estimated to be 1448m/s from the slope of Fig. 4b) and gradually reduces to a normal sound speed at the distance of ~ 1.09 mm.

Fig. 4. Photoacoustic Smith-Purcell Radiation in the near-field. (a) Experimental measurement of the temporal evolution of laser-induced plasma shock wave. By a specially designed He-Ne laser interferometer, we could detect the shock wave's propagating distance versus propagating time in (b). (b) presents the averaged experiment data (blue cubes) and the theoretical near-field curve (red, based on Sedov-Taylor model). In the far-field (which is beyond 1.09mm in our setup) the induced shock wave drops to conventional sonic acoustic wave (black). The insert presents a real-time shock wave signal received at 0.52mm from the shock wave source with a delay time of 727ns. (c)-(f): a 2D CFD numerical simulation for the near-field case: Four snapshots of air pressure distribution in simulation cell (0.3x0.8mm) at time step: 280ns, 380ns, 470ns, and 550ns. Four cylindrical scatters (white disk) collide with an incoming vertical plane shock front with a velocity of 750m/s. Pressure detectors line up along the x-axis, e.g. point P, which traces the coming shock wave (c), 1st (d), and 2nd scattered shock waves (f) versus time in (g). Fig. (h) Blue dots show the time lag between the two scattered shock waves acquired from the CFD simulation. The red curve represents a theoretically calculated time delay based on the Sedov-Taylor model in Eq. 3. While the black line parallel indicates the time delay $\Delta t = 192$ ns in the far-field, i.e. sonic regime. T_1 and T_2 are the arrival time for 1st and 2nd scattered shock waves separately. ΔT is the intrinsic time delay for shock wave passing through the adjacent cylinders, determined by the velocity of the shock wave.

Such change in propagation speed dramatically distinguishes photoacoustic SPR from its photonic counterpart, in which the speed of light always keeps a constant value. In this regard, it is meaningful to discuss photoacoustic

SPR in two separated regimes: the far-field and the near-field cases, depending on the detector's position whether inside the supersonic zone (Fig. 4b). In the above experiment, the microphone is placed far away ($>2\text{cm}$) from the laser shock wave spot, outside the shock wave's supersonic zone with a radius around 1.09mm . In this case, the short supersonic traveling length of the shock in the near field is almost negligible as compared to the total path between the plate and the microphone in the far-field, hardly affecting the phase delay between two successive wavefronts as shown in Eq. 1. Hence, this far-field situation exactly resembles its photonic analogy with a constant speed of light.

In contrast, the near-field case of photoacoustic SPR is quite distinguishable from the far-field case. In the supersonic zone, the shock wave excited by the laser-plasma spark travels at a velocity beyond the sound speed, a simplified Sedov-Taylor model equation $R(t) = at^b$ can describe the temporal evolution of the propagation distance (a, b is the parameter related to the Sedov-Taylor model in Eq. 2. Consequently, when a strong shock wave passes by a grating structure (Fig. 1), each grating tooth scatters the shock wave sequentially, the resulted Smith-Purcell formula in the supersonic near field can be derived accordingly as:

$$\Delta t_m(D, \cos \theta, s) = \underbrace{\left(\frac{s - m \cdot D \cdot \cos \theta}{a} \right)^{\frac{1}{b}}}_{T_m} - \underbrace{\left[\frac{s - (m-1) \cdot D \cdot \cos \theta}{a} \right]^{\frac{1}{b}}}_{T_{m-1}} + \Delta T \quad (3)$$

where Δt_m is the m -th time delay between two adjacent wavefronts when arriving upon the detector. T_m is the traveling time from the m -th scatter to the detector, and $\Delta T = D/v$ is the intrinsic time delay for neighboring scattering teeth (assuming a uniform velocity v). The distance between the grating and the detector s is comparable to the grating period D in the near field, but $s \gg D$ in the far-field. Obviously, the time delay Δt_m would *not be a constant value* in the near field, particularly depending on m 's order. This sharply contrasts with the far-field situation, where the constant time delay gives rise to a fixed-frequency SPR, i.e., $\Delta t_m = \Delta T$ if $s \gg D$.

Due to the lack of a laser source with a higher repetition rate to excite all laser sparkles within one supersonic zone, instead, we perform a numerical study for the near-field photoacoustic SPR using a commercially available computational fluid dynamics tool (CFD)[36]. As shown in Fig. 4c-f, a vertical plane shock with an initial velocity of 750m/s is launched from the left, propagating to the right direction and encountering a grating array composed of four inline cylindrical scatters with a periodicity of $45\mu\text{m}$, which is smaller than supersonic zone. Accordingly, a series of detector points to measure shock wave line up in a backward direction (180°). For instance, Detector P is placed within the supersonic zone, near the leftmost cylinder (Fig. 4c). From the recorded time trace in Fig. 4g, a sequence of shock waves and corresponded scattered shock waves are observed. However, the simulated time delays (Fig. 4h) between the two leftmost adjacent scatters versus detector distance are not even, varying from 150ns to 200ns , in direct contrast with the far-field case, where a constant time delay is expected instead. For the further detector beyond $78\mu\text{m}$, such time delays are mostly enlarged to around 192ns . This transition from the near-field case to the far-field one can be more clearly demonstrated in the theoretical curves based on Eq. 3 with an additional quadratic modification for a weak shock condition, which depicts the time delay gradually reaches a flat constant floor when the detector approaches further distance.

Similar to photonic SPR with undulator configuration, the photoacoustic SPR can also be tailored for particular acoustic wave emission in terms of bandwidth, frequency, and emission angle by engineering micro-structured grating. In this manner, a compact acoustic wave source with dispersive spreading frequency emission can be

obtained, similar to an optical grating, which might be beneficial for some acoustic spectroscopy applications[37]. Meanwhile, acoustic SPR is not limited to free space, also applicable for bulk conditions, e.g. exciting phonons within layered materials[38]. For example, it has been proposed to generate THz waves using semiconductor superlattices by considering SPR based phonon-photon interactions[39]. These photo-excited phonons have been well studied using ultrafast laser pulsed for their propagation, interaction[28,40]. We believe this acoustic version of the Smith-Purcell effect may finally open a new avenue in condensed matter, acoustics, phononics.

In conclusion, we have demonstrated a new type of photoacoustic SPR based on laser-induced shock waves. The inherent excitation mechanisms of photoacoustic SPR shares the same root as its photonic counterpart, as a result, the observed radiation pattern and spectrum can be well described by a universal theory working both for the photonic and acoustic cases. However, the current work reveals a striking observation of none-uniform time delay due to the supersonic traveling of shock waves only in the near field regime. We believe similar studies can be further extended to other physical systems like phonons in the solid-state system.

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