Laser-induced quasiperiodic mode hopping in competing ionization waves

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A neon glow-discharge plasma supports, among various traveling and standing modes of oscillation, multimode oscillation in the form of traveling normal modes of *p*-type neon-ionization waves each distinguished by the fixed number of half-wavelengths present in the tube. The modes compete as coupled spatiotemporal oscillators, each capable of driving the other or being driven. Competition is modulated by neon-resonant laser light chopped almost synchronously with a subdominant wave mode, resulting in quasiperiodic mode hopping between neighbor wave modes. This process repeats indefinitely without adjustment of the discharge plasma or chopped laser light parameters. The oscillator-amplitude normalization of the driving force term in the driven van der Pol oscillator equations, which is critical to the physical mechanism of mode-competition modulation, as explained here, is experimentally demonstrated during the quasiperiodic mode hopping and shown to be responsible for the observed toggling between the driver- and oscillator-amplitude values and the alternating mode identity of the driver and oscillator. *Acknowledgments: The glow-discharge tube and inspiration for this project was provided by Dr. K.-D. Weltmann of the Leibniz-Institute for Plasma Science and Technology (INP) in Greifswald, Germany. Funding was provided by NSF grant PHY-0613238 (P.M. and M. K.), DOE grant DE-FG02-06ER46267 (H.G), and DOE grant DE-SC0001939 (M.K.).*

For the conditions of the neon glow discharge tube described here, pressure $P = 200$ Pa (1.5 Torr), $R = 1.0$ cm, and discharge currents from 3 mA to 15 mA. The waves described here are *p* waves [1]. Since the radius of the tube is 1.0 cm, and mode frequency ranges from 0.5 kHz to 2.5 kHz, the reduced parameters of this tube are $pR = 1.5$ Torr-cm, 3 mA/cm $< I/R <$ 15 mA/cm, and 0.5 cm-kHz $< Rf <$ 2.5 cm-kHz.

At one set of discharge conditions, a single mode dominates in the family of the traveling *p*-

type normal modes of neon-ionization waves. One or more unidirectional mode hops take place in sequence as conditions are sufficiently changed to make dominant a different mode. During the brief event of a mode transition, pre-transition dominant mode and post-transition dominant mode coexist, interacting in time and space, with the ratio of wave amplitudes rapidly passing from one extreme, through unity, to the other extreme [2]. Quasiperiodic mode hopping refers to recurring bidirectional mode transitions. In this work, the role of oscillation-amplitude normalization of the driving-force amplitude in the driven van der Pol equations is shown to be responsible for toggling the driver amplitude and oscillator values, which in turn, toggles the mode identity of the driver and oscillator. Chopped neon-resonant laser light is used to induce this toggling by recurrent perturbation of the normalized driving-force amplitude of one wave mode acting on a neighbor wave mode [3].

Frequency spectra contain signatures from wave-to-wave interaction and from chopped-laser-light-to-wave interaction involved in the mode-competition modulation cycle. Distinguishing modulation dynamics from instantaneous-frequency (instantaneous-wavevector) and instantaneous-beat-frequency (instantaneous-beat-wavevector) time series is easier than from time-averaged frequency (wavevector) spectra or wavelet transforms because of improved time and frequency resolution possible when only two or three modes interact.

The data for this study were time series from the photodiode, which responded to the oscillations of the luminous ionized gas in the discharge tube. This time series was recorded with sufficient time resolution (typically 100 kS/s for 1 s), and multiple realizations were recorded for each driving frequency [4].

The instantaneous frequency is determined from signal time series by inverting the period between pairs of zero crossings spaced an oscillation period apart. The instantaneous beat frequency is determined in the same way from the instantaneous-frequency time series. These time series document the alternating dominance in two competing ionization waves, confirm proper normalization of the effective driving-force amplitude in the explanation of the observed quasiperiodic mode hopping, and establish the plausibility of a driven-oscillator mechanism for toggling the identity of the dominant mode. The results correct and refine the dynamics modulation explanation put forward by Weltmann, Koepke, and Selcher [1].

Optical forcing was accomplished using a Coherent 899 ring dye laser, operated with

Rhodamine 6G dye as a gain medium, pumped with an Innova 90 Plus Argon-Ion laser, and tuned to wavelengths near the metastable neon transition at 588.35 nm [5]. This vacuum wavelength corresponds to 588.19 nm in air and represents the $2s^22p^5$ ($^2P_{3/2}$)3s to $2s^22p^5$ ($^2P_{1/2}$)3p transition [6]. In the older Paschen notation commonly used in discharge physics, this is represented as $1s_5$ -- $2p_5$ [7].

The laser was capable of delivering the necessary driving force when operated at a power between 100-150 mW (as measured just outside the laser cavity's output coupler). Laser power was monitored and the position of the laser beam and optics relative to the discharge tube was not adjusted during the experiment in order to ensure a constant absolute driving-force amplitude. The beam was passed through an acousto-optic modulator (AOM), and then was directed toward the discharge tube so that the first-order AOM output line was incident at a point inside the discharge tube 2.5 cm from the cathode where coupling to the plasma was measured to be excellent. (See Figure 8 in [1]) A photodiode detector was placed at a position 57.5 cm from the cathode and aimed at the center of the discharge through a 640.1 nm, 4 nm bandwidth filter. The photodiode detector was elevated so that its axis was at a height matching the axis of the tube. The distance between the detector and the tube was adjusted so that light from the center of the tube would be focused onto the photodiode.

We number the modes according to frequency starting with f1 for the mode with the smallest observable frequency. As discharge current is increased, the dominant-mode frequency will exhibit slight discharge-current dependence and then suddenly change in discrete reproducible steps that exhibit hysterisis. Here, we consider the f7 ≅ 1.44 kHz and f8 ≅ 1.72 kHz modes. The discharge current is set so that the f7 mode is strongly favored in the absence of the chopped neon-resonant laser beam.

Examine what happens during a mode-competition-modulation cycle, starting when the higher mode f8 and lower mode f7 wave-wave coupling has been suddenly interrupted. Higher-frequency f8 wave mode, subdominant at this time, is sustained by being temporally driven by the chopped laser beam at chopping frequency fL. Lower-frequency f7 wave mode, dominant at this time, is weakly driven by the chopped laser beam at fL. Both f8 wave mode and f7 wave mode drive each other and toggle their identity as dominant mode. During the cycle, subdominant f8 wave mode is pulled by the chopped laser beam downward partway toward the chopping frequency fL, over which time the periodic pulling of dominant f7 wave mode by subdominant f8 wave mode strengthens, the depth of frequency modulation increases, and the upward dominant-mode hop from dominant f7 wave mode to dominant f8 wave mode takes place. Higher f8 wave mode is now dominant, sustained by having entrained the f7 wave mode transiently, and is subject to subdominant f7's normalized driving-force amplitude striving to pull dominant f8 further downward toward subdominant f7. At the end of the periodic pulling beat note of the chopped laser beam driving the f8 wave mode, the interaction between the chopped laser beam and the dominant f8 wave mode interrupts and restarts with a subdominant f8, simultaneously the interaction between f7 wave mode and f8 wave mode interrupts and restarts, and the downward dominant-mode hop switches the dominant-mode identity. The chopped laser beam negligibly drives the f7 wave mode.

We have measured the relevant normalized driving-force amplitude values and found that, previous to the downward mode hop, the f7 wave mode drives the f8 wave mode stronger than, previous to the upward mode hop, the f8 wave mode drives the f7 wave mode. Smaller still is the amplitude at which the chopped laser beam drives the f8 wave mode throughout the mode-competition modulation cycle.

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