Observation of Two-Photon Photoemission Enabled by Early GaAs Laser Diodes from MIT Lincoln Laboratory (1964)

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Early GaAs laser diodes, generously provided by Bob Keyes, Ted Quist, and Al McWhorter of MIT Lincoln Laboratory when I began my doctoral research at Cornell University, enabled the observation of two-photon photoemission in 1964. A more extensive discussion appears in: *LED Lighting: Devices and Colorimetry* by M. C. Teich (SPIE Press, Bellingham, WA, 2025): https://spie.org/Publications/Book/100371

This contribution highlights the early two-photon photoemission work carried out in the course of my doctoral research at Cornell University, during the period 1963–1966 [1]. The experiments I conducted were enabled by the GaAs laser diode, developed contemporaneously at GE, IBM, and MIT Lincoln Laboratory in 1962 [2]. Several of these devices were generously provided to me by Lincoln Laboratory researchers Bob Keyes, Ted Quist, and Al McWhorter. Use of the device portrayed in Fig. 1 enabled me to experimentally observe two-photon photoemission from sodium metal in 1964 [3,4], as well as to demonstrate the phenomenon of dc photomixing [1,5]. Two-photon photoemission was one of the earliest nonlinear-optical effects to be documented. Some forty years later, the temperature and wavelength dependence of two-photon photoemission from bialkali semiconductors was analyzed [6], and entangled two-photon photoemission was observed [7].

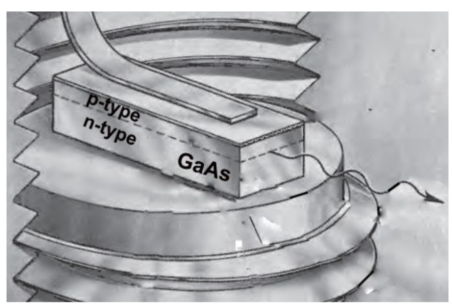

Figure 1. Artist's rendering of GaAs laser diode LD256 fabricated at MIT Lincoln Laboratory in 1963. The width and length of the semiconductor regions were 200 μm and 1 mm, respectively. When operated in pulsed mode at 77 K, this device emitted coherent light at 845 nm [2]. (Image adapted from Fig. 3 on p. 16 of [1].)

Months before having developed the laser diode, Keyes and Quist (Fig. 2) pioneered the first truly useful light-emitting diode [8]. As they reported in July 1962 [9], their GaAs LED, operating CW at room temperature, emitted spontaneous recombination radiation with a peak wavelength of 920 nm, in the near-infrared. Despite its wavelength, the light from their new LED was visible — it appeared red to the human eye [9]. I vividly recall my own surprise upon observing red emission from their GaAs laser diode, which operated at liquid-nitrogen temperature and emitted 845-nm coherent radiation.

Figure 2. **Robert J. Keyes (1927–2012)** and **Theodore M. Quist (1931–2013)**, left and right, respectively, displayed the high-efficiency, *p–n* junction light-emitting diode they co-invented while working at MIT Lincoln Laboratory in 1962. Operated at room temperature, this direct-bandgap GaAs semiconductor device generated spontaneous recombination radiation with a peak wavelength at $\lambda = 920$ nm in the near-infrared. (Courtesy Robert J. Keyes, MIT Lincoln Laboratory.)

As discussed in [10], a substantial body of research, dating to the time of von Helmholtz, has demonstrated that the perception of light by humans extends over a wavelength range far greater than the usually recognized range, which is 380–780 nm. In experiments carried out with lasers operated at five different near-infrared wavelengths, Sliney [11] reported in 1976 that the photopic luminous efficiency function $V(\lambda)$, when plotted on semilogarithmic coordinates so the tails of the curve could be resolved, extended over a far broader range of wavelengths, namely 310–1100 nm (the details vary with the radiance of the source and there is variation among individual observers). Sliney further reported that all wavelengths in the 625–1100 nm range appear red to the normal human observer, thereby confirming the original observations of Keyes and Quist.

These early interactions led me to join MIT Lincoln Laboratory in 1966 for my first professional position, in Group 82 under Bob Keyes (Associate Group Leader) and Bob Kingston (Group Leader), with Al McWhorter heading Division 8. My initial project at Lincoln Laboratory focused on implementing heterodyne detection in the mid-infrared, employing the then-new CO_2 laser in conjunction with a Ge photoconductive detector [12,13]. The two detection modalities — heterodyne detection and two-photon direct detection — were subsequently unified by considering two-photon heterodyne photodetection, which admits dc photomixing [14].

Much of this is discussed in my recently published book:
M. C. Teich, *LED Lighting: Devices and Colorimetry*, SPIE Press (Bellingham, WA, 2025).

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