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2 The long journey to the laser and its use for nonlinear optics

Abstract: Einstein introduced the basic principle of the laser in 1917. However, the possibility of light amplification was not recognized for decades. Eventually, Maiman from the Hughes Aircraft Co. realized the first laser based on ruby as active medium. This unexpected result excited our group at the Bell Labs and we realized the first intense and highly directional (<1 degree) laser beam. On October 5, 1960 we demonstrated the red laser beam fired from the radar tower in New Jersey and its detection 25 miles away. The new light source initiated the field of Nonlinear Optics (NLO). We realized the first two-photon fluorescence in 1961.

The title of this article suggests a substantial history of the laser. For you the laser is a well-known and well-established optical light source. But please note, that the laser started its existence just 55 years ago.

In 1900, Max Planck published a theory about the experimentally known black body radiation [1]. In his derivation he introduced the light quantum $E = hf$ for the transition between two energy states. This revolutionary idea was used by the – then young – Einstein in 1917 in a completely different derivation of the same black body radiation [2]. In this paper the basic principle of the laser was introduced: the stimulated emission of light. An excited quantum state can be de-excited by a passing light quantum of the proper frequency, i.e., two photons leave the system or – in other words – the stimulating photon is amplified. During the following decades the process of stimulated light emission received surprisingly little attention in the scientific community. In a few papers the dispersion of light in excited gases was investigated and named negative dispersion. The possibility of light amplification was not recognized for 34 years.

Finally, in 1951, Charles Townes, a professor at Columbia University in New York and consultant at the Bell Laboratories had the ingenious idea to build a microwave amplifier (with ammonia gas at 1.25 cm) using the stimulated excitation process. It is interesting to read in the biography of Townes how he found the maser (microwave amplifier by stimulated emission of radiation). He was on his way to a meeting concerning new microwave amplifiers. He knew that no proposals existed. Under a certain pressure the idea occurred to him to study the stimulated light emission process quantitatively for the application in a new device. In fact, in 1953 the first maser was in operation. The desirable extension to higher frequencies – preferentially to the visible – was first discussed theoretically by Schawlow and Townes in 1958 [3]. Tab. 2.1 provides an overview of the historical development of the maser and laser.
Tab. 2.1: Overview of the historical development of the maser and laser.

<table>
<thead>
<tr>
<th>Year</th>
<th>Inventor(s)</th>
<th>Event</th>
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<tbody>
<tr>
<td>1900</td>
<td>Planck</td>
<td>Quantum of radiation $E = hf$</td>
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<tr>
<td>1917</td>
<td>Einstein</td>
<td>absorption, emission, stimulated emission</td>
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<td>1923</td>
<td>Tolman</td>
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<td>1927</td>
<td>Ladenburg</td>
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<tr>
<td>1941</td>
<td>Fabrikant</td>
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<tr>
<td>1951</td>
<td>Townes</td>
<td>MASER</td>
</tr>
<tr>
<td>1952–55</td>
<td>Townes</td>
<td>Microwave Amplification by Stimulated Emission of Radiation</td>
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<td></td>
<td>Basov</td>
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<td></td>
<td>Prokhorov</td>
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<tr>
<td>1958</td>
<td>Schawlow</td>
<td>LASER</td>
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<td></td>
<td>Townes</td>
<td>Theory: <em>Physical Review</em> 112, 1940 (1958)</td>
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T. H. Maiman [4], a physicist at the Hughes Aircraft Co., realized the first laser based on ruby as active medium. He talked on the new light source during a press conference in New York on July 7, 1960. The newspaper *New York Times* reported on it one day later. The first scientific paper “Stimulated optical radiation in ruby” was published in *Nature* in August 6, 1960. Maiman pumped a ruby crystal with a powerful flash lamp and observed narrowing of the emitting beam to 55 degrees. The beam was delivered through a hole in the silver coating.

This unexpected result excited our group at the Bell Laboratories to repeat the ruby experiment. After three weeks we saw the expected extremely intense, highly directional (<1 degree) beam of coherent highly narrowed radiation and sent a manuscript on our findings to the journal *Physics Review Letters* on August 26, 1960 ([5], Fig. 2.1).

There was no doubt: This observation was a true laser emission as expected from theory. We used a semitransparent silver coating instead of a hole for out-coupling. On October 5, 1960 we gave a press conference (Fig. 2.2) and demonstrated a red beam of the new light source, fired from the radar tower in New Jersey and detected 25 miles away at Crawford Hill using a photomultiplier (Fig. 2.3 and 2.4).

The same year, the He:Ne gas laser became operational at Bell [6] and the 4-level-laser was introduced [7, 8].

The very strong light emission by the new light source laser initiated the field of Nonlinear Optics (NLO). In 1961, second harmonic radiation was found in non-centrosymmetric crystals (e.g. quartz) by Franken et al. at the University of Michigan [9] and by Giordmaine at Bell [10]. First two-photon fluorescence was seen in Eu$^{3+}$CaF$_2$ by Kaiser and Garrett at Bell [11].
Schawlow and Townes\(^1\) have proposed that, with a sufficiently great inverted population density in a radiating assembly of atoms, enclosed in a suitable cavity, stimulated emission of light will occur cumulatively, leading to (1) decrease in lifetime, (2) spectral line narrowing, (3) coherence in the electromagnetic field, and (4) sharp directionality of the radiation leaving a Fabry-Perot cavity. The use of a ruby rod for the observation of these effects has been proposed by Schawlow.\(^2\) Recently Malman\(^3\) has observed a decrease of the lifetime and a narrowing of the through the silvered ends and from the sides of the rod. The light was allowed to fall on the entrance slit of a Jarrell-Ash 78-400 grating spectrometer adequate to resolve the \(R_1\) and \(R_2\) lines, occurring at wave numbers 14,400 cm\(^{-1}\) and 14,450 cm\(^{-1}\), respectively. The output of the photomultiplier detector was displayed on a dual-beam oscilloscope. The collector circuit time constant was of the order of 10\(^{-9}\) second. Under low excitation conditions the oscilloscope traces showed simply the expected fluorescent rise and decay [Fig. 1(a)], the ratio of the intensity of the

Bell Telephone Laboratories, Murray Hill, New Jersey  
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Fig. 2.1: Publication in *Physics Review Letters* on the first stable laser by Collins, Nelson, Schawlow, Bond, Garrett, and Kaiser on October 1, 1960 (manuscript received on August 26, 1960) [12].

Fig. 2.2: Press conference on October 8, 1960. Reused with permission of Nokia Corporation [13].
While we studied the two-photon transition, we learned that already in 1927 a theoretical paper was written on the same topic by Mrs. Göppert in Göttingen/Germany. She calculated correctly that the probability to see two-quantum transitions is too small for the light sources existing at her time. With our powerful laser light we saw the two-quantum transition quite readily in good agreement with her calculations. In 1961 I called her up and told that we were able to prove her theory of two-photon transitions using the laser. However, at that time her research focused on the nuclear shell.

**Fig. 2.3:** First presentation of a stable laser beam to the public. Williard Boyle and Robert Collins “fired” the ruby laser from the radar tower at Murray Hill, close to the Bell Labs, to Crawfort Hill in New Jersey, 25 miles away, where it was detected by Walter Bond and Donald Nelson. Reused with permission of Nokia Corporation [13].

**Fig. 2.4:** The ruby laser beam from Bell Labs was highly directional (< 1°) and therefore more intense than the first laser beam by Maiman at Hughes Aircraft Co.
During the past 55 years the number of new lasers has increased to an impressive number and the number of general laser applications has grown tremendously. Besides high speed data communication, industrial fabrication and environmental monitoring, only two further topics should be cited here. First, femtosecond laser spectroscopy is applied to study the fast carrier dynamics in semiconductors as well as primary reactions in photosynthesis (Fig. 2.5). With respect to regenerative energy sources it is worth mentioning that the yearly turnover of photosynthesis is $2 \times 10^{18}$ kJ on earth which corresponds to the six-fold primary energy needed currently by humans. Second, new medical laser applications have significant value for our health. Especially diagnoses of eyes and skin – discussed further in this book – are of great importance for all of us. In 1963 Dr. Goeppert-Mayer received the Nobel Prize for theoretical physics [13, 14]. Further information and the development of the laser can be obtained from references [13] and [14].

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**References**


