Introduction of Laser Principle

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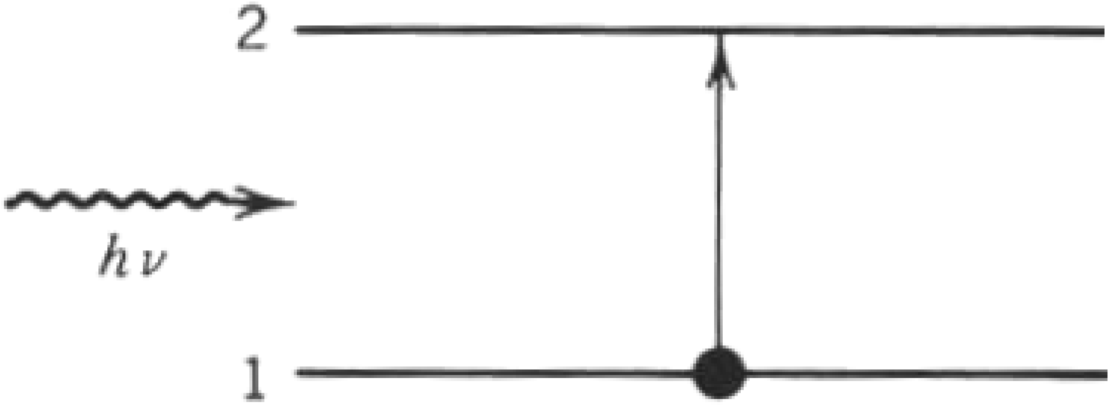
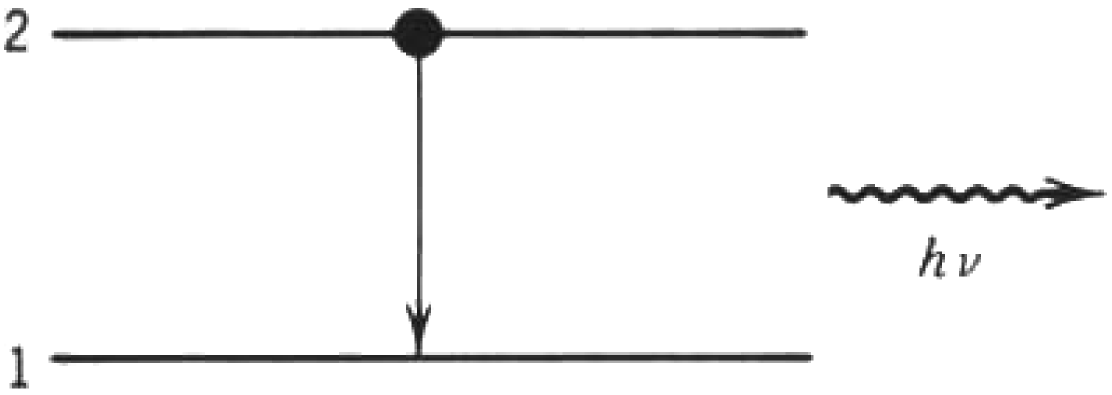
Laser의 특성

- 단색성
- 고휘도
- 지향성
- 가간섭성(Coherency)

흡수와 자발방출



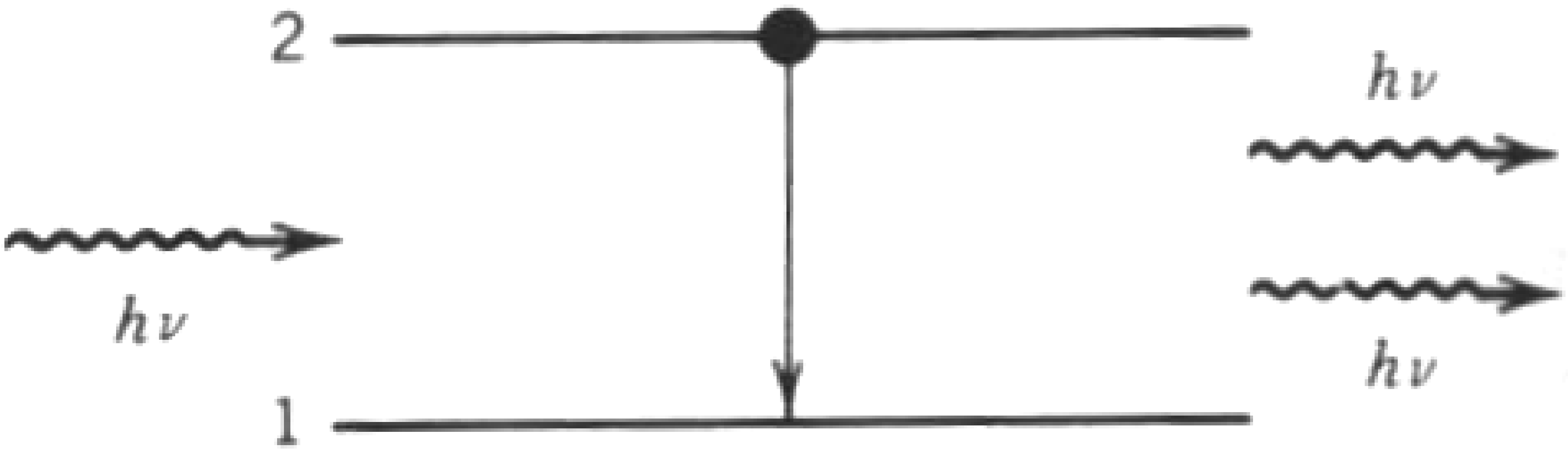
❿흡수(Absorption)



❿자발방출

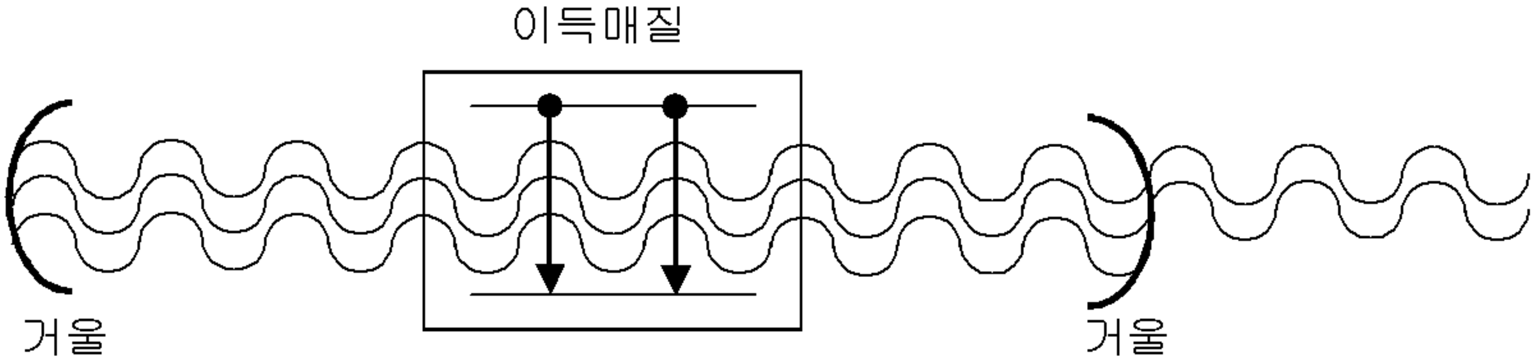
❿(Spontaneous Emission)

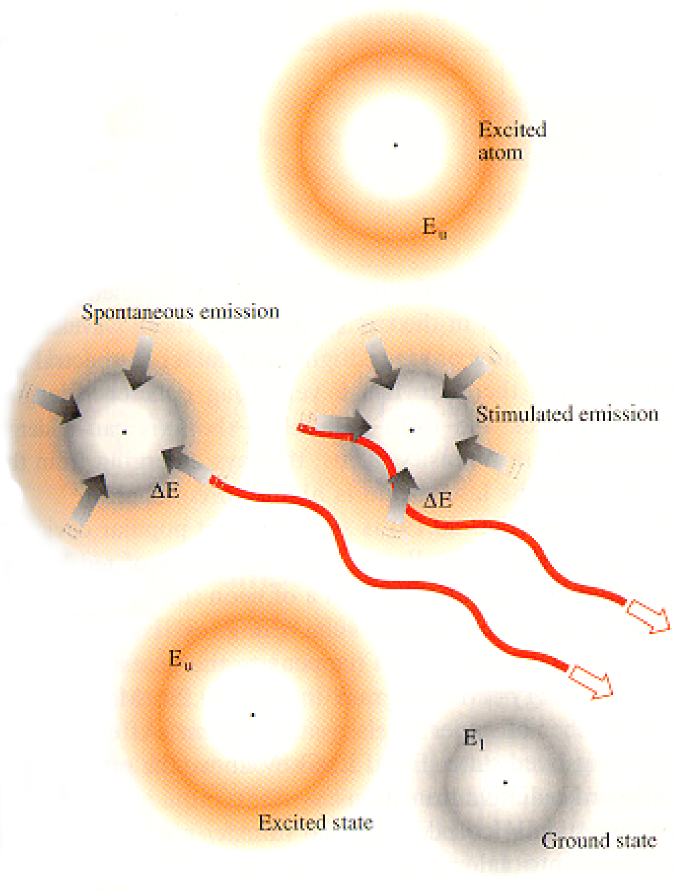
유도방출(Stimulated Emission)

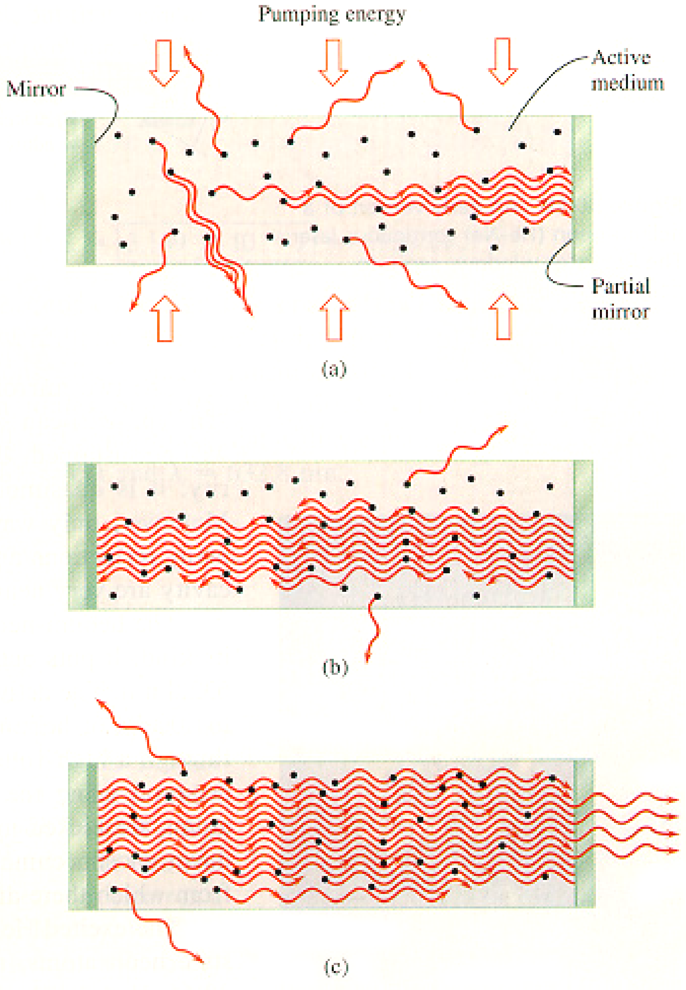


LASER

Light Amplification by Stimulated Emission of Radiation

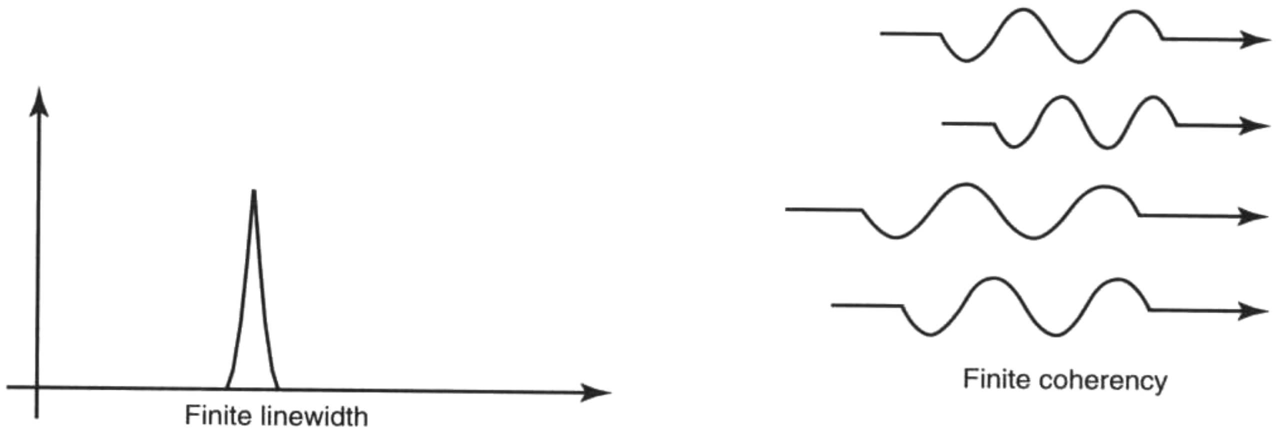



Excited atom
E_u
Spontaneous emission
Stimulated emission
ΔE
ΔE
E_u
E_l
Excited state
Ground state


Pumping energy
Mirror
Active medium
Partial mirror
(a)
(b)
(c)

Coherency

An ideal monochromatic source of light has a group of photons with exactly one frequency.
An ideal coherent source of light has a group of photons with the same relative phase.

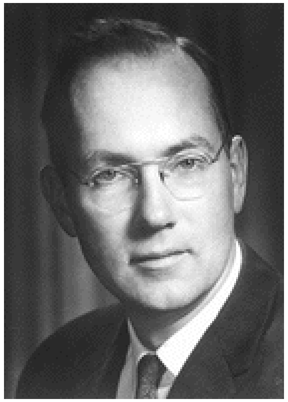


Real laser sources are neither perfectly monochromatic nor perfectly coherent.
A real laser will have a finite linewidth and finite coherency.

Laser의 역사

- 1917 Einstein – Stimulated Emission
- 1940s Fabrikant – 박사학위 논문
- 1950s Townes, Weber, Prokhorov, Basov - MASER
- 1954 Gordon, Townes, Zeiger – 최초의 maser
- 1957 Gould – LASER 특허출원
- 1958 Schawlow, Townes – “Intrared and Optical Masers” 논문
- 1960. 5. 16. Maiman – 최초의 레이저 동작 (Ruby laser)
- 1960. 12. 12. Javan, Bennett, Herriott – 최초의 cw 레이저 동작 (He-Ne laser)
- … laser flood

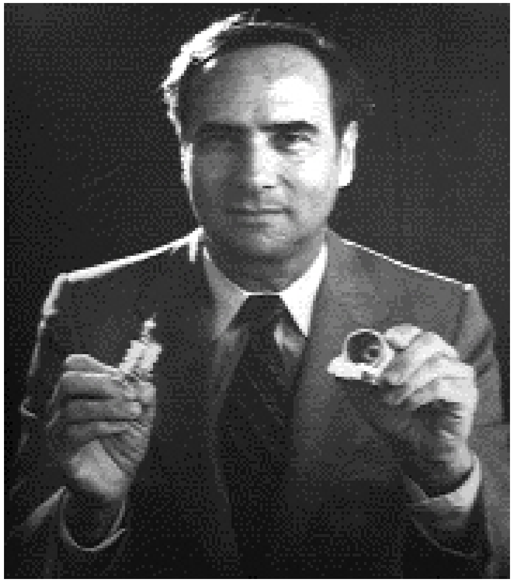
Laser가 늦게 발명된 이유



Charles H. Townes (1915-)

"대부분의 물리학자들은 전자공학과 증폭기에 대해서 몰랐었고, 전기공학자들은 대개 양자역학을 배우지 않았다. 하지만 제 2차 세계대전으로 인해 레이다(radar) 개발을 위해 공학자들과 자연과학자들이 함께 일하게 되었고, 물리학자들이 전자공학에 접근할 수 있게 되었다."

최초의 레이저 – Ruby Laser



- 최초의 레이저 : 1960년, Maiman이 만든 세계 최초의 레이저, 루비를 레이저 매질로 사용

Theodore Harold Maiman
1927-2007
Theodore Maiman, who demonstrated the world’s first laser in May 1960, passed away on May 5, 2007, at the age of 79.

Other groups had already started trying to build lasers when Maiman decided to tackle the problem in mid-1959. He owed his quick success to a particularly elegant design and a keen understanding of the properties of the material he used, synthetic ruby.

Small enough to fit in his hand, the ruby laser worked on the first try—a rarity in cutting-edge research made possible by Maiman’s knowledge of physics and his knack for engineering. The ruby laser changed the course of laser development; unlike the other types being developed at the time, it concentrated its power into pulses. Engineers soon tested pulsed lasers by blasting holes in razor blades and measuring their power in “gillettes” (the number of razor blades through which the laser could burn a hole). Physicists used pulsed lasers to discover new optical effects. Charles Townes, who received the 1964 Nobel Prize in physics for developing the maser-laser principle, called Maiman’s laser “an important start to a tremendously important field of science and technology.”

Born in Los Angeles and raised in Denver, Colo., Maiman learned electronics from his father, Abe Maiman, an electrical engineer for AT&T Corporation. After serving in the Navy, Theodore Maiman studied engineering physics at the University of Colorado and physics at Stanford under the theoretician Willis Lamb, who received the Nobel Prize in physics in 1955, months after Maiman received his doctorate.

Maiman settled at Hughes Research Laboratories, a California aerospace contractor owned by billionaire Howard Hughes. It was a hotbed of innovation, fueled by the Cold War military budget and powered by a staff of bright, intense and often colorful scientists. To keep ideas simmering, Hughes lured the famed physicist Richard Feynman from Caltech to give regular seminars.

Townes earlier had invented the maser, a microwave predecessor of the laser, at Columbia University in New York. Hughes’s managers assigned Maiman to build a more practical version of the maser using microwave emission from chromium atoms in synthetic ruby crystals. An earlier version had weighed more than two tons, but Maiman built a ruby maser that weighed only two kilograms.

Maiman then turned his attention to the laser, proposed separately by Townes and Gordon Gould. Bell Labs and the Pentagon’s Advanced Research Projects Agency had funded competing million-dollar programs to build lasers, but progress had stalled on the issue of finding a material that could store energy briefly, then be stimulated to emit the energy as a beam of light. Others had dismissed using ruby, claiming it didn’t emit light efficiently enough. However, Maiman decided to see where the lost energy was going. He found that the earlier measurements were wrong.

Using his own data, Maiman calculated that he could make a marginal laser by illuminating a ruby rod with the most intense movie projector lamp on the market. Seeking a better demonstration, he decided to try exciting the laser with bright pulses of light, and his student assistant Charles Asawa suggested using a photographic flash lamp. Maiman then ordered three sizes of spring-shaped flashlamps, and started tests on the smallest. He inserted a fingertip-sized ruby rod inside the coiled lamp, then sealed the lamp and rod inside a machined aluminum cylinder.

Maiman and his assistant Irnee D’Haenens hooked up a power supply and measured pulses as they slowly cranked up the voltage. They saw the red ruby pulses suddenly grow brighter as the power crossed the threshold for producing a laser beam. It was a moment of triumph after months of intense effort.

Maiman presented an important report on the laser at an OSA meeting in fall 1960 [(paper TC1, “Stimulated optical emission in ruby,” JOSA 50, p. 1134 (Nov. 1960)]; this may have been his first description of a laser at a scientific conference.

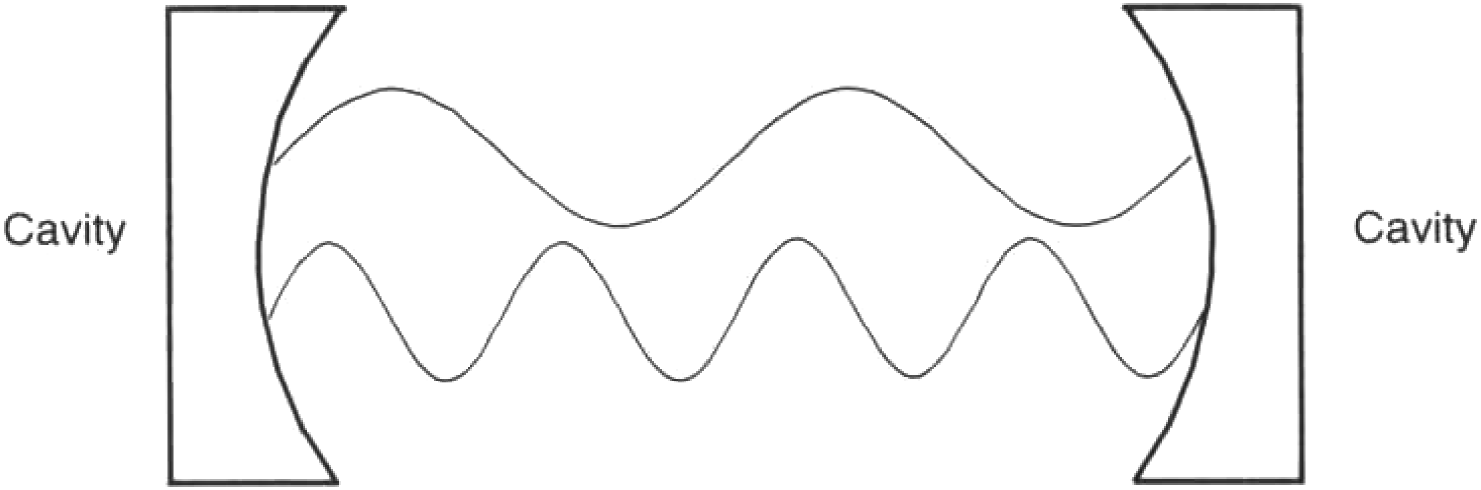
Maiman left Hughes less than a year after making the first laser, founding a company called Korad, which he headed for several years before being bought out. He later was a consultant for the aerospace firm TRW.

Throughout his career, Maiman received several scientific awards, including the Fannie and John Hertz Science Award, the 1984 Wolf prize, and the 1987 Japan prize. In 1976, Maiman received OSA’s R.W. Wood Award, which recognizes outstanding discovery, scientific or technical achievement, or invention.

He was twice nominated for the Nobel Prize and was given membership in both National Academies of Science and Engineers. He received the 1983/4 Physics Prize and was inducted into the National Inventors Hall of Fame.

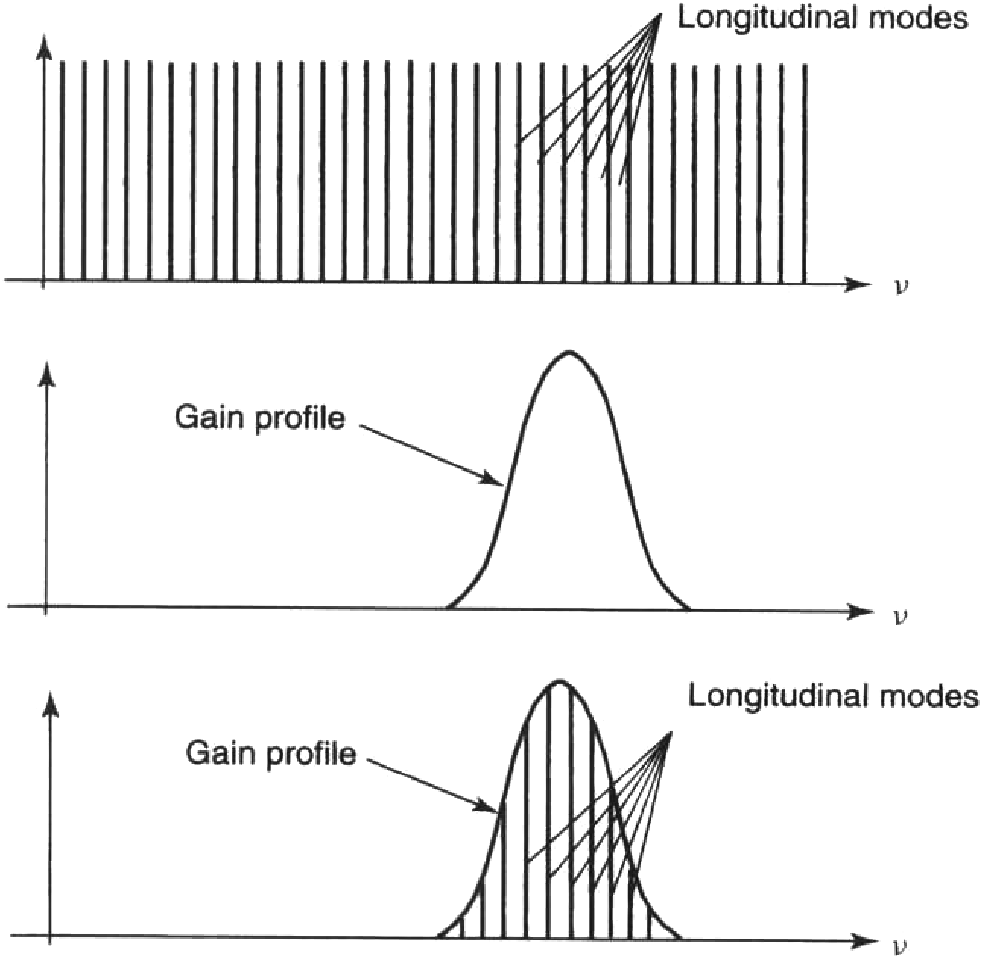
--Jeff Hecht
This tribute is adapted from an obituary that was published May 9, 2007, in the British newspaper The Independent.

Laser oscillation (1)

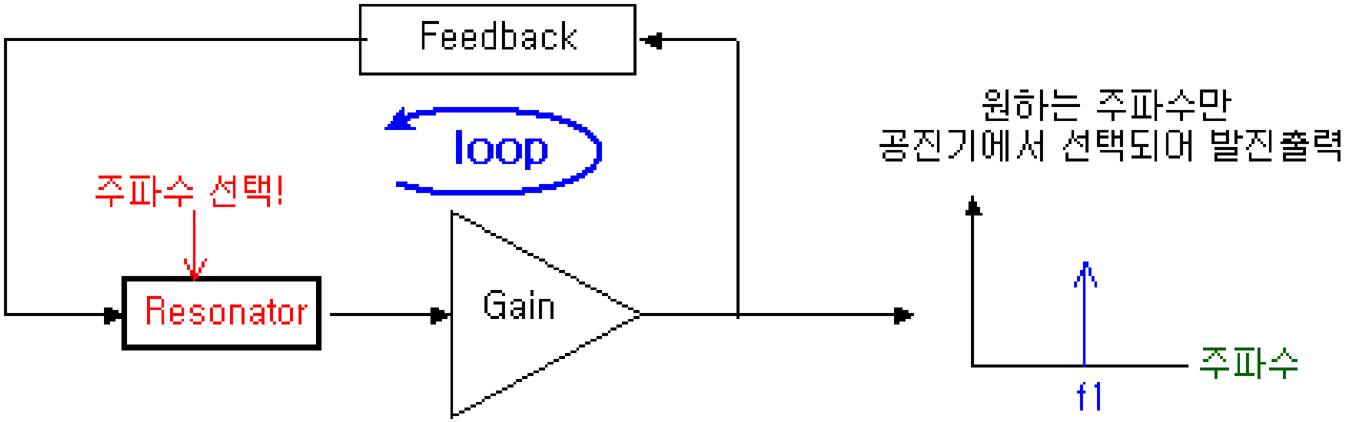


A laser can only lase at those wavelengths (longitudinal modes) for which an integral multiple of half-wavelengths fit into the cavity.

Laser oscillation (2)

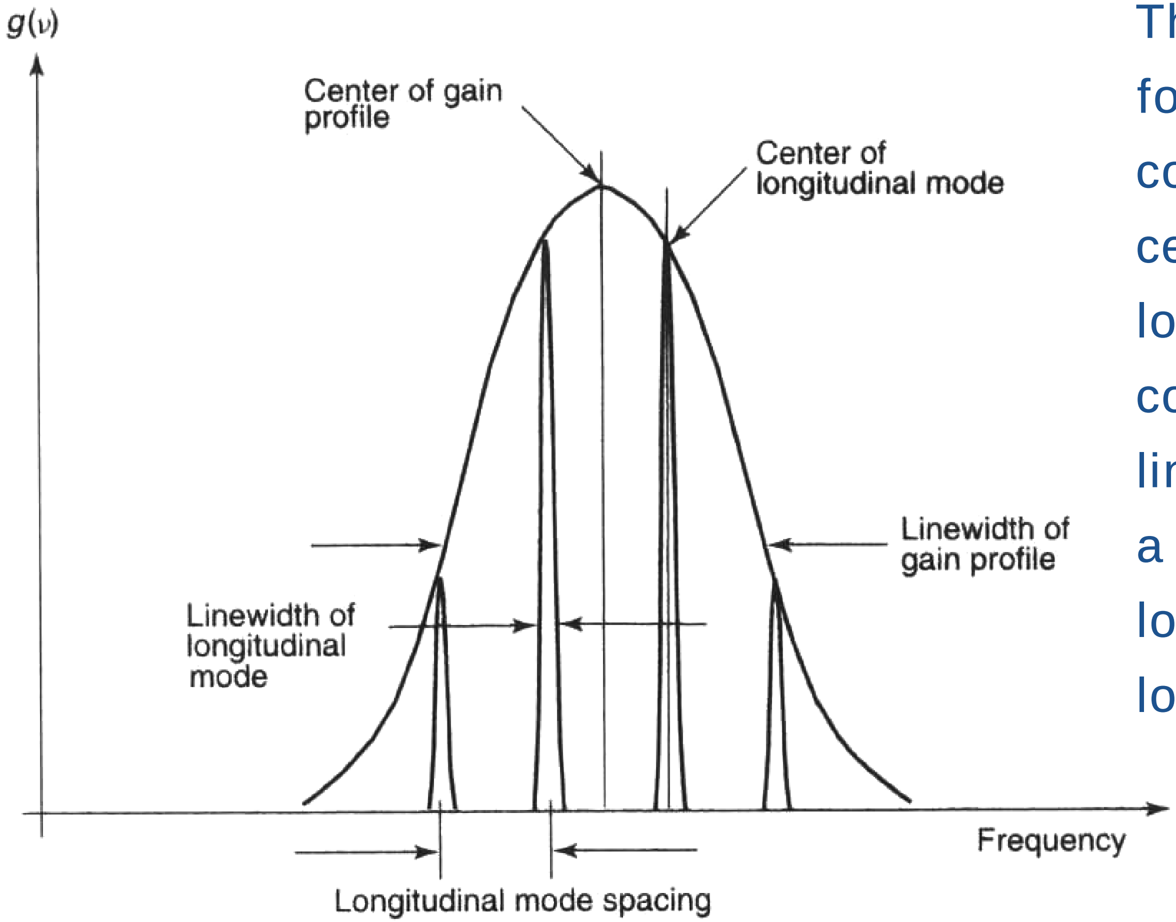


발진회로와의 비교



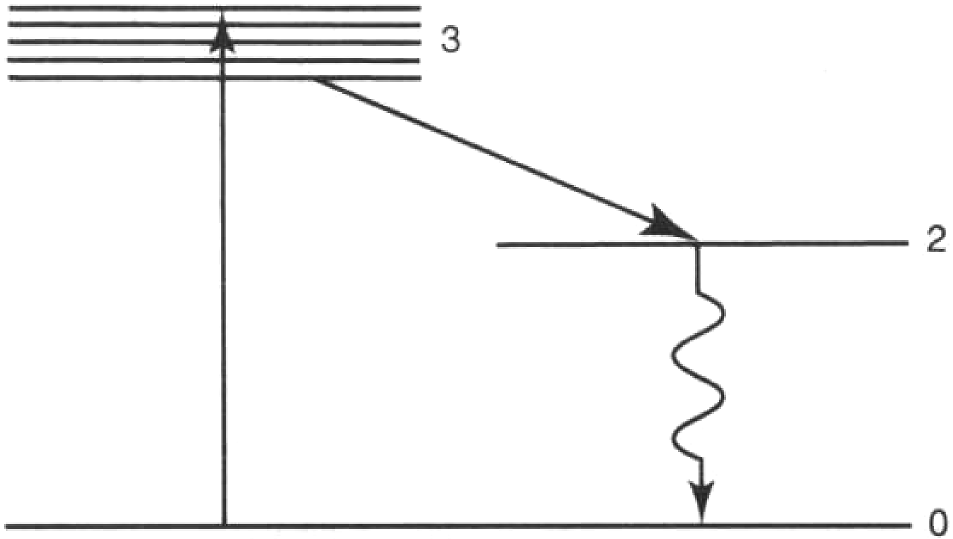
- ❖ Gain = 이득매질
- ❖ Feedback & 주파수선택 = 공진기 (거울)

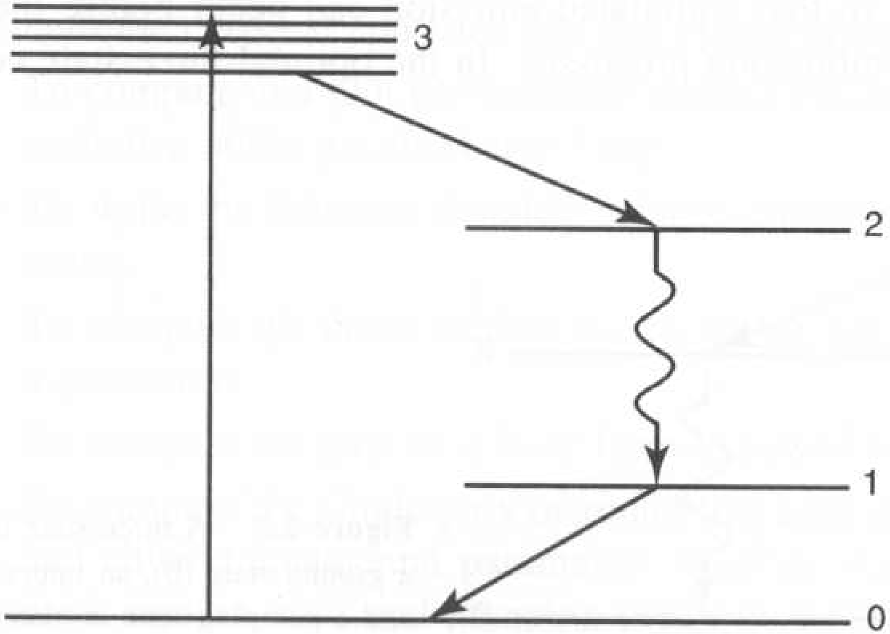
Lasing mode(s)



There is a center wavelength for the gain profile and its corresponding frequency, a center wavelength for each longitudinal mode and their corresponding frequencies, a linewidth for the gain profile, a linewidth for each longitudinal mode, and a longitudinal mode separation.

3-level and 4-level laser systems





A three-state laser consists of a ground state(0), an upper laser state(2), and a pumping state or states(3).

A four-state laser consists of a ground state 0, a pumping state(or band of states) 3, an upper laser state 2, and a lower laser state 1.

Linewidth Broadening

- Homogeneous broadening
  - Lifetime broadening
  - Collision broadening

- Inhomogeneous broadening
  - Doppler broadening

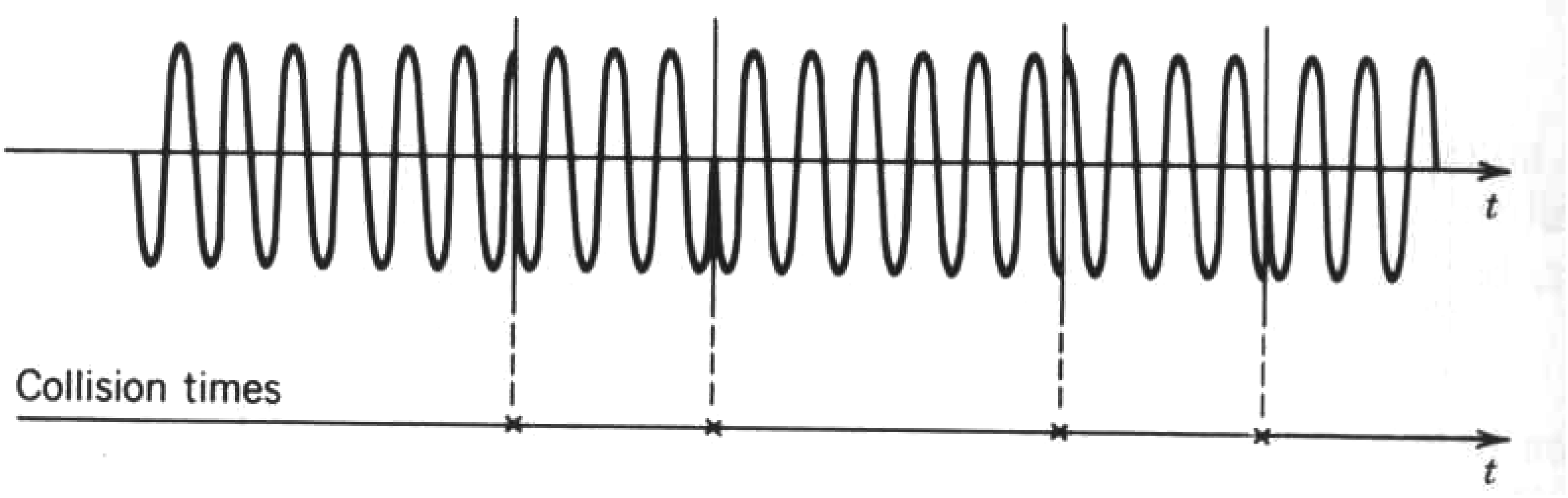
Lifetime Broadening

$$\Delta\nu = \frac{1}{2\pi}\left(\frac{1}{\tau_1} + \frac{1}{\tau_2}\right)$$

$$g(\nu) = \frac{\Delta\nu/2\pi}{(\nu - \nu_0)^2 + (\Delta\nu/2)^2}$$

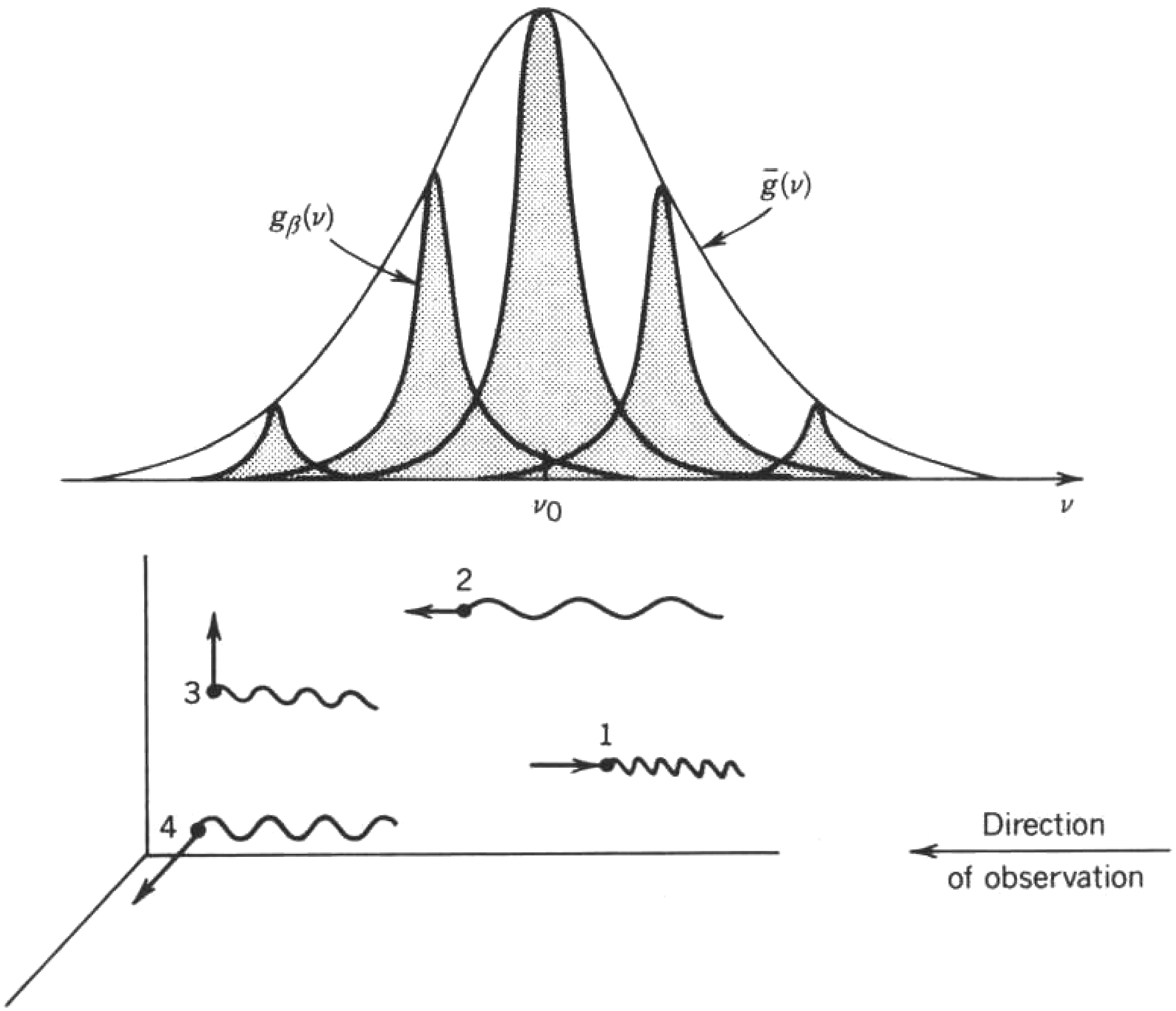
Lorentzian lineshape function

Collision Broadening



$$\Delta\nu = \frac{1}{2\pi}\left(\frac{1}{\tau_1}+\frac{1}{\tau_2}+2f_{\text{col}}\right)$$

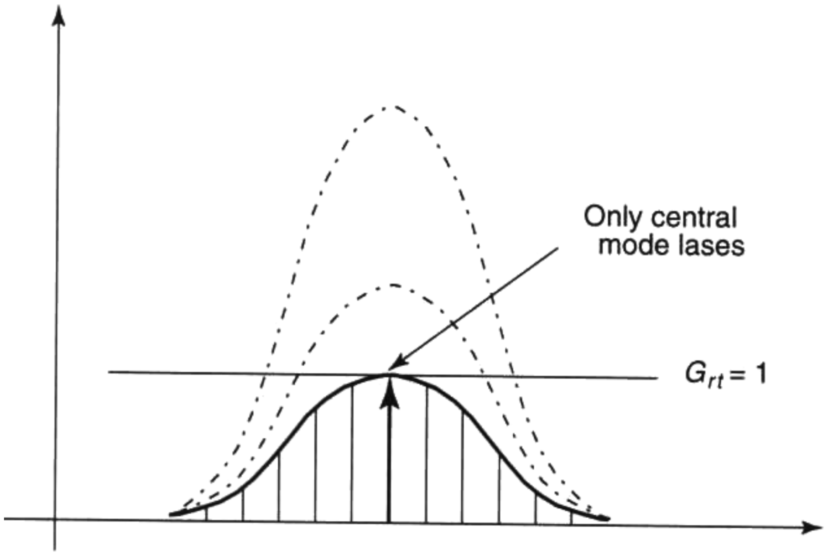
Inhomogeneous Broadening

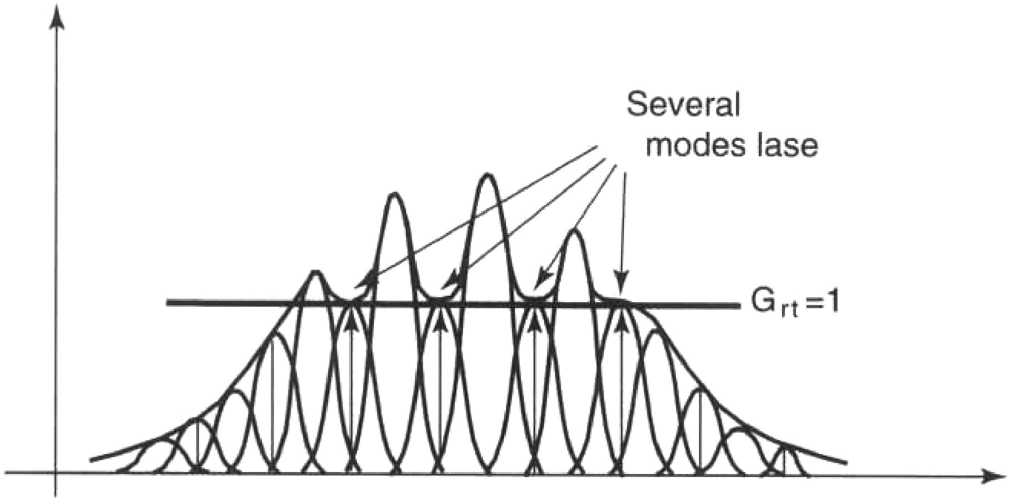


Gaussian lineshape

Doppler broadening

Homogeneous-Broadening Laser vs. Inhomogeneous-Broadening Laser





In a homogeneous laser, the entire gain saturates proportionally. As a consequence, only the central longitudinal mode can sustain a round trip gain of 1.

In an inhomogeneous laser, saturation at one particular frequency causes a reduction in the gain profile only near that frequency. Effectively, holes are burned in the gain profile such that the frequencies corresponding to the longitudinal modes are precisely at threshold.

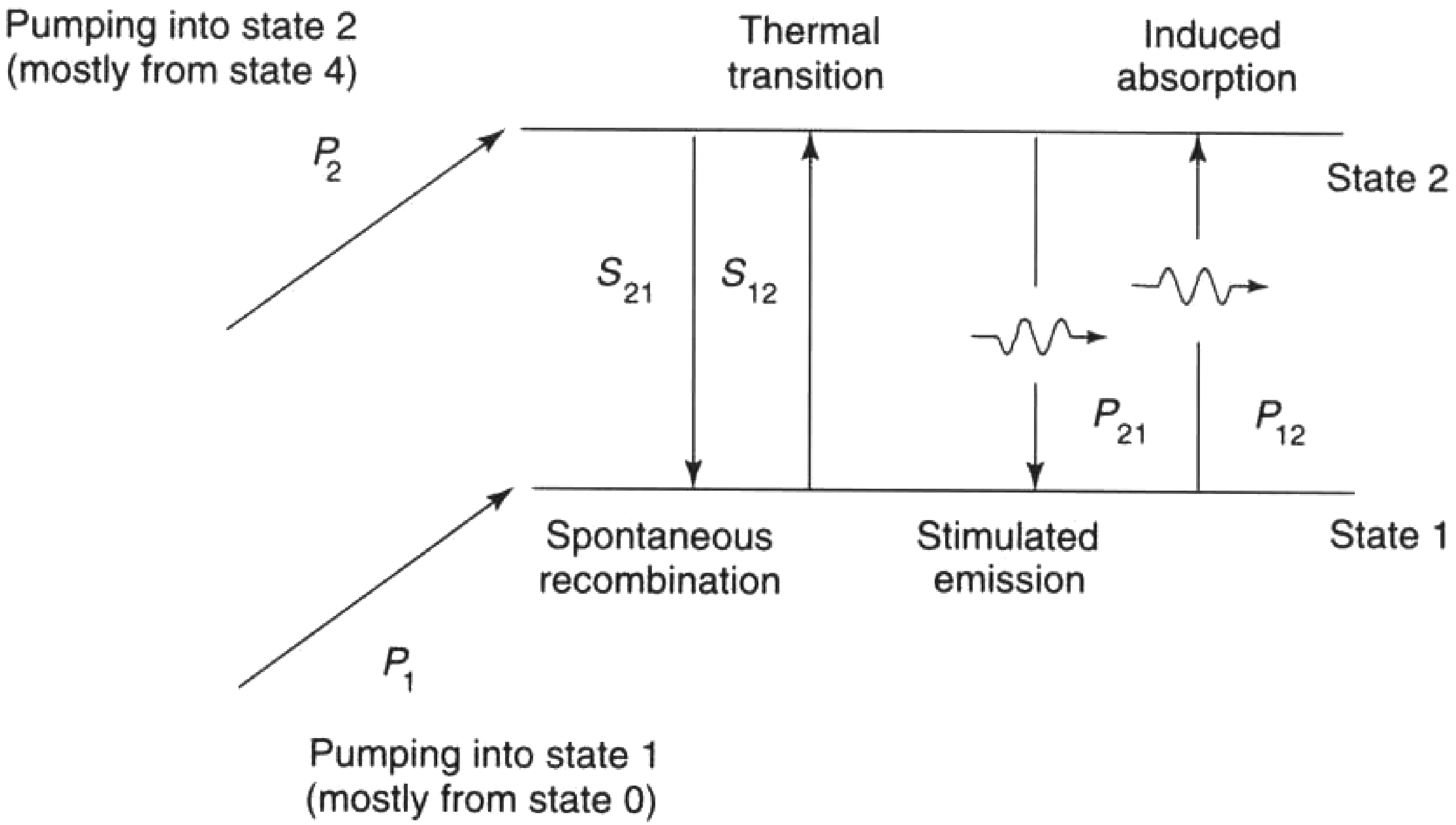
Gain

$$\gamma(v) = g(v)\left(\frac{A_{21}\lambda_0^2}{8\pi n^2}\right)\left(N_2 - N_1\left(\frac{g_2}{g_1}\right)\right)$$

$$R_F R_B e^{2\gamma(v)L} \geq 1$$

$$\gamma(v) \geq \frac{1}{2L} 1n\left(\frac{1}{R_F R_B}\right)$$

Diagram for Rate Equations

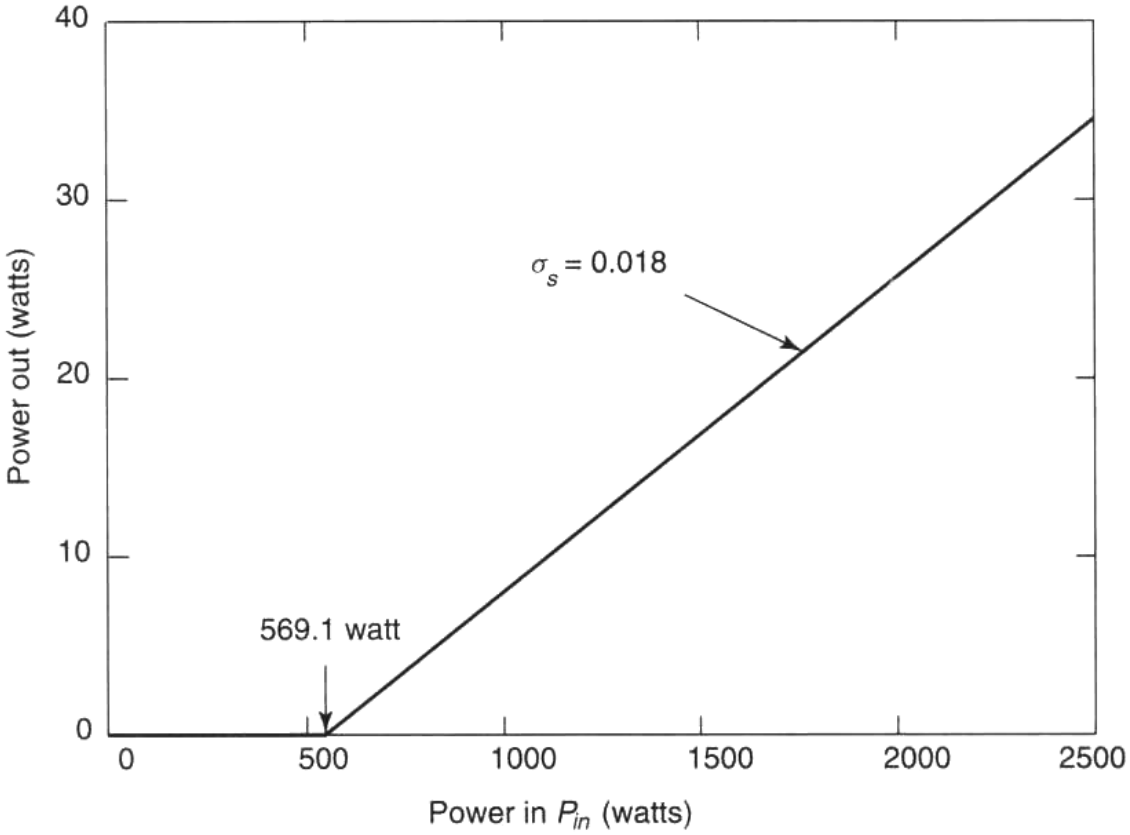


Gain Saturation

$$\gamma(\nu) = \frac{\gamma_0(\nu)}{1 + \frac{I}{I_{sat}}}$$

$$I_{sat} = \left(\frac{8\pi h n^2 \nu^3}{g(\nu) A_{21} c_0^2 \tau_2}\right)\left(\frac{1}{1 + \frac{\tau_1}{\tau_2}\left(1 - \frac{\tau_2}{\tau_{21}}\right)}\right)$$

레이저의 커브의 예

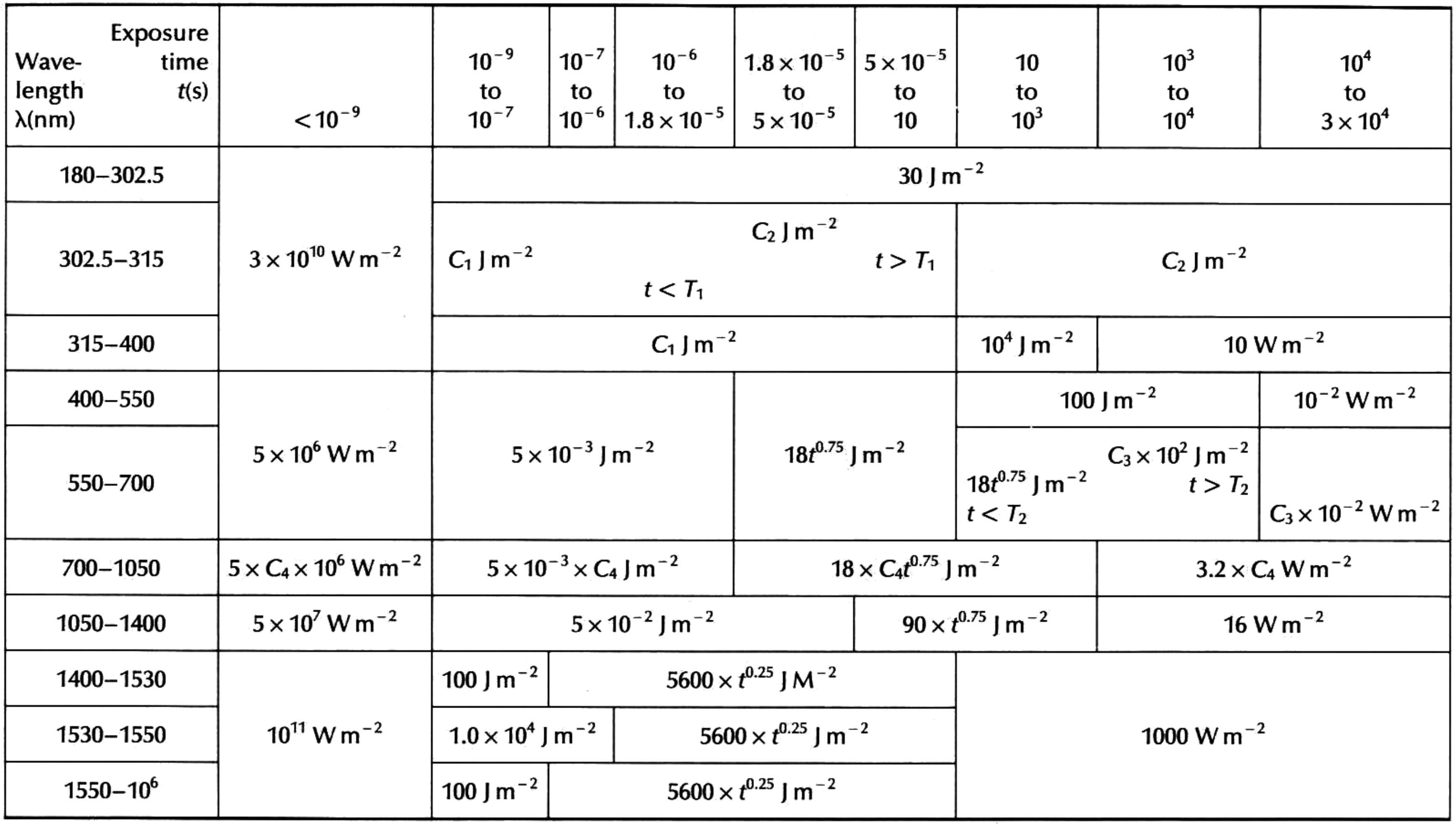


40
30
20
10
0
Power out (watts)
$\sigma_s = 0.018$
569.1 watt
0
500
1000
1500
2000
2500
Power in P_{in} (watts)

Laser safety (1)

	Hazard	Control
Class 1	The output is so low that the laser is inherently safe Or The laser is totally enclosed and it is safe by engineering design.	No control other than labelling
Class 2	These are visible CW and pulsed lasers where the protection can be afforded by the blink reflex of 0.25 s.	The laser head must be labeled. The beam should be terminated. No beams at eye level.
Class 3A	Class 2 is extended to exclude viewing with optical instruments.	Extra caution than class 2.
Class 3B*	This is a sub-class of 3B confined to visible lasers with less than 5 mW CW output.	Treated like 3A.
Class 3B**	Eye hazard from intra-beam viewing and from specular reflections.	A designated laser area and interlocks must be used. Eye protection required for exposed beams. Beam terminated.
Class 4	Hazard from diffuse reflection and possibly to skin	As for Class 3B** Protective clothing recommended.

Laser safety (2)



Wave-length λ(nm) / Exposure time t(s)	$< 10^{-9}$	10^{-9} to 10^{-7}	10^{-7} to 10^{-6}	10^{-6} to 1.8×10^{-5}	1.8×10^{-5} to 5×10^{-5}	5×10^{-5} to 10	10 to 10^3	10^3 to 10^4	10^4 to 3×10^4
180–302.5	3×10^{10} W m^{-2}	30 J m^{-2}							
302.5–315		C_1 J m^{-2} $t < T_1$ C_2 J m^{-2} $t > T_1$					C_2 J m^{-2}		
315–400		C_1 J m^{-2}					10^4 J m^{-2}	10 W m^{-2}	
400–550	5×10^6 W m^{-2}	5×10^{-3} J m^{-2}			$18t^{0.75}$ J m^{-2}		100 J m^{-2}		10^{-2} W m^{-2}
550–700							$18t^{0.75}$ J m^{-2} $t < T_2$ $C_3 \times 10^2$ J m^{-2} $t > T_2$		$C_3 \times 10^{-2}$ W m^{-2}
700–1050	$5 \times C_4 \times 10^6$ W m^{-2}	$5 \times 10^{-3} \times C_4$ J m^{-2}			$18 \times C_4 t^{0.75}$ J m^{-2}			$3.2 \times C_4$ W m^{-2}	
1050–1400	5×10^7 W m^{-2}	5×10^{-2} J m^{-2}				$90 \times t^{0.75}$ J m^{-2}		16 W m^{-2}	
1400–1530	10^{11} W m^{-2}	100 J m^{-2}	$5600 \times t^{0.25}$ J M^{-2}				1000 W m^{-2}		
1530–1550		1.0×10^4 J m^{-2}		$5600 \times t^{0.25}$ J m^{-2}					
1550–10^6		100 J m^{-2}	$5600 \times t^{0.25}$ J m^{-2}						

References

K. J. Kuhn, *Laser Engineering*, Prentice Hall, New York, USA, 1998.

J. Hawkes and I. Latimer, *Lasers – Theory and Practice*, Prentice Hall, New York, USA, 1995.