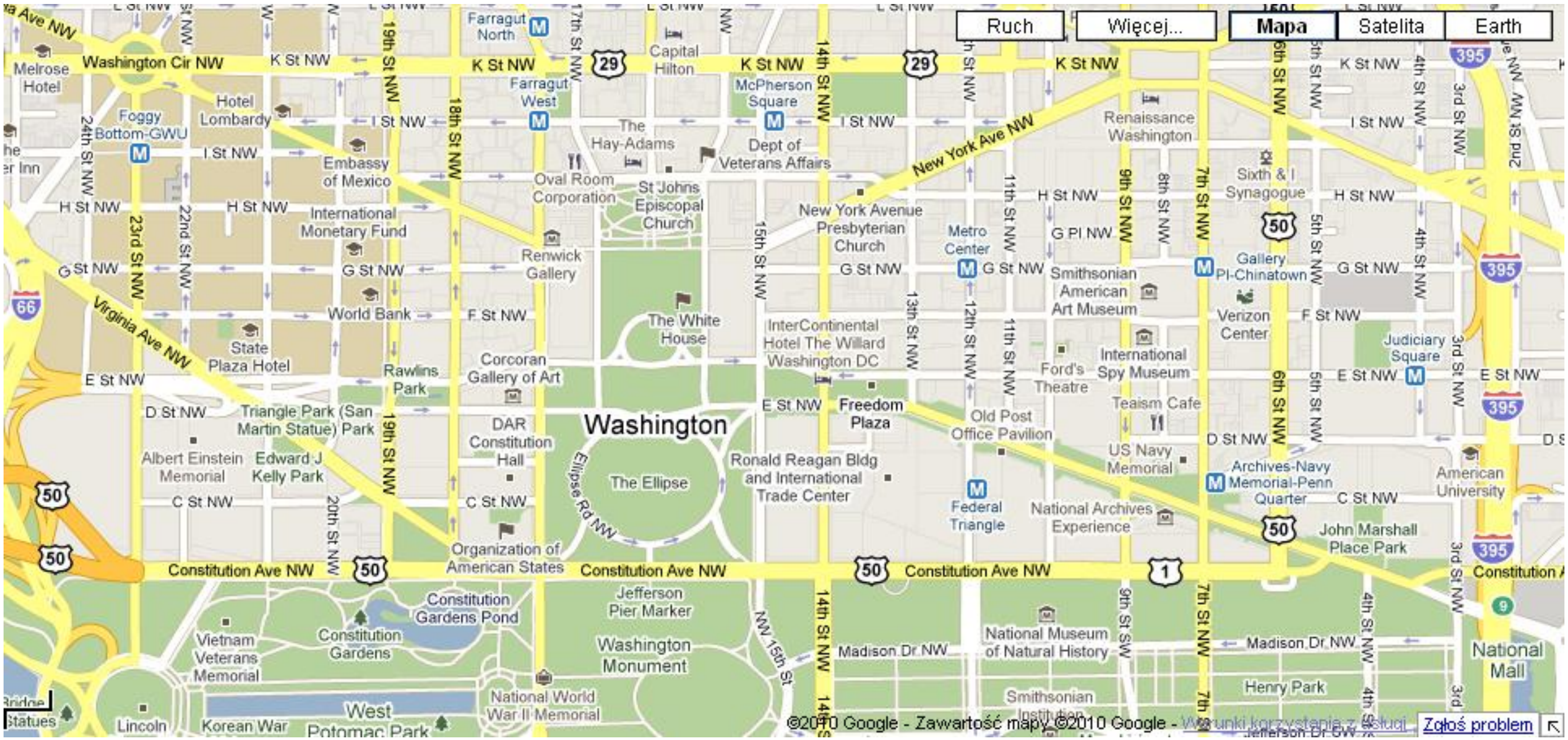
Laser – wstęp do idei

Laser – pół wieku

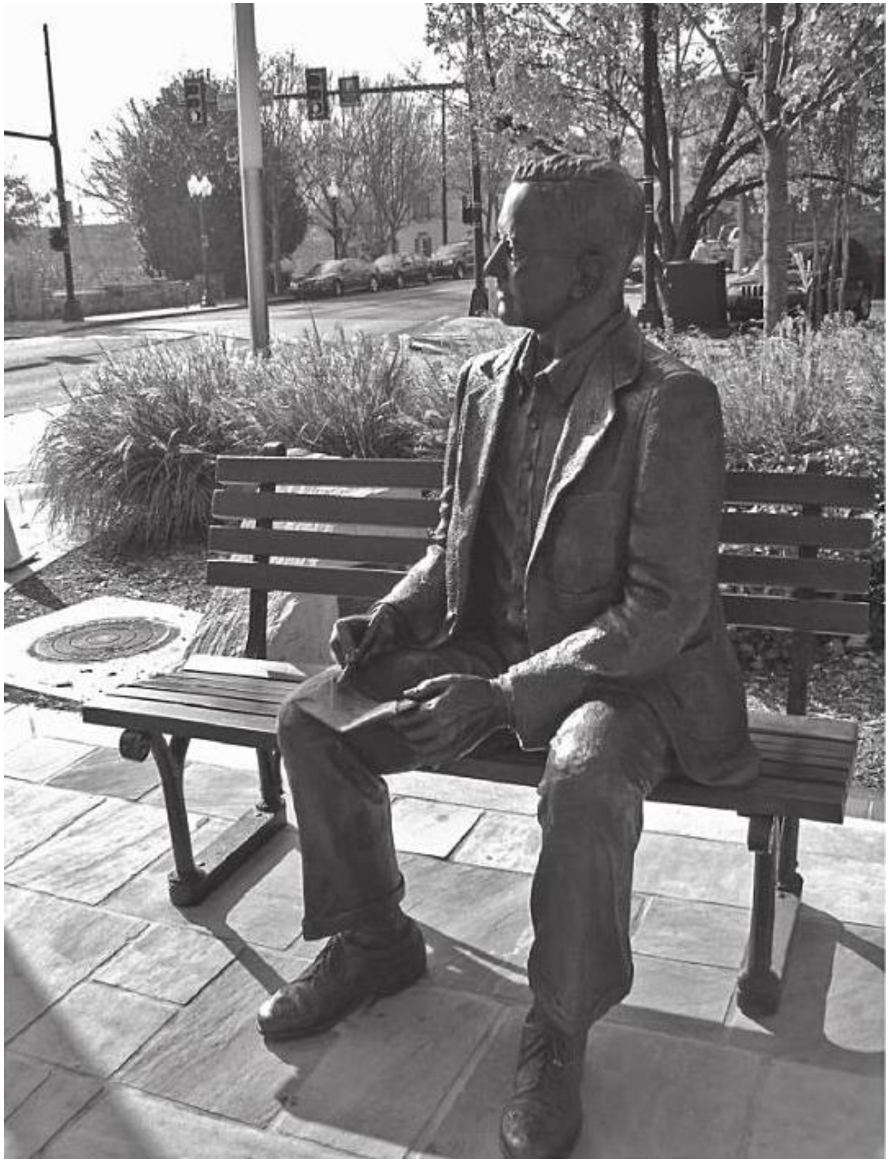
- Maser – Townes 1955
- pompowanie optyczne w gazie: Gordon Gould (U.S. patent 4,161,436), Charles Townes and Arthur Schawlow (Phys. Rev. **112**, 1940 (1958))
- Ali Javan (Bell Labs) *"Possibility of producing negative temperature in gas discharge"*, Phys. Rev. Lett. **3**, 87 (1959)
- J. H. Sanders (Oxofrd, Bell) *"Optical maser design"*, Phys. Rev. Lett. **3**, 86 (1959)
- 16 maja 1960, Theodore Maiman, Hugher Research, pierwszy laser (rubinowy)
- 13 grudnia 1960, Javan, Benett, Herriott, pierwszy laser He-Ne, 1153 nm
- 1962, pierwszy czerwony He-Ne
- 1963, CO_2 10,6 μm, 1965 – 200 W CW
- 14 lutego 1964, argonowy 488 nm
- 1966, 50 kW CO_2

Początki

26 kwietnia 1951, Franklin Park, Washington

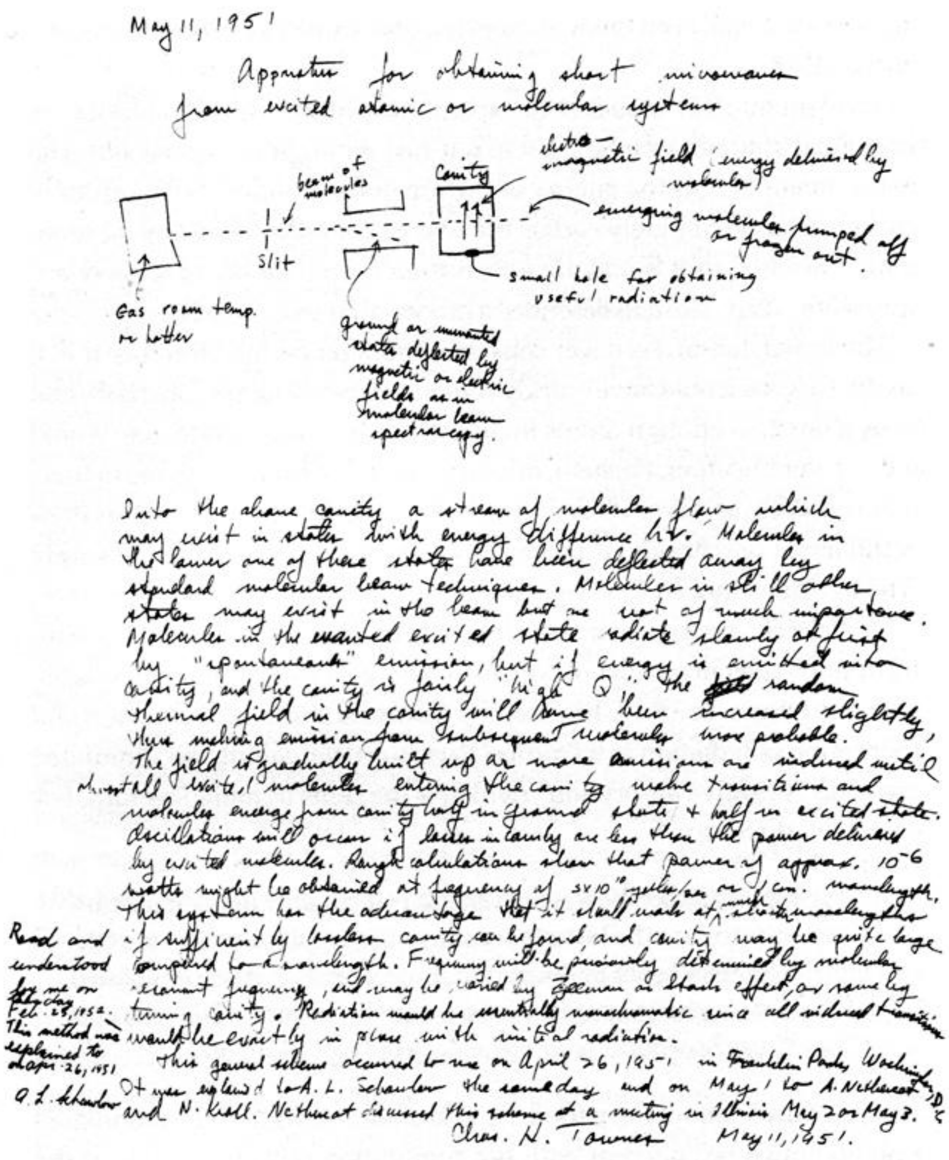


Townes



Townes Square, Downtown, Greenville

Labbook Townesa, 11 maja 1951



May 11, 1951

Apparatus for obtaining short microwaves from excited atomic or molecular systems

beam of molecules
Cavity
electro-magnetic field (energy delivered by molecules)
emerging molecules pumped off or frozen out.
Slit
small hole for obtaining useful radiation
Gas room temp. or hotter
ground or unwanted state deflected by magnetic or electric fields as in molecular beam spectroscopy.

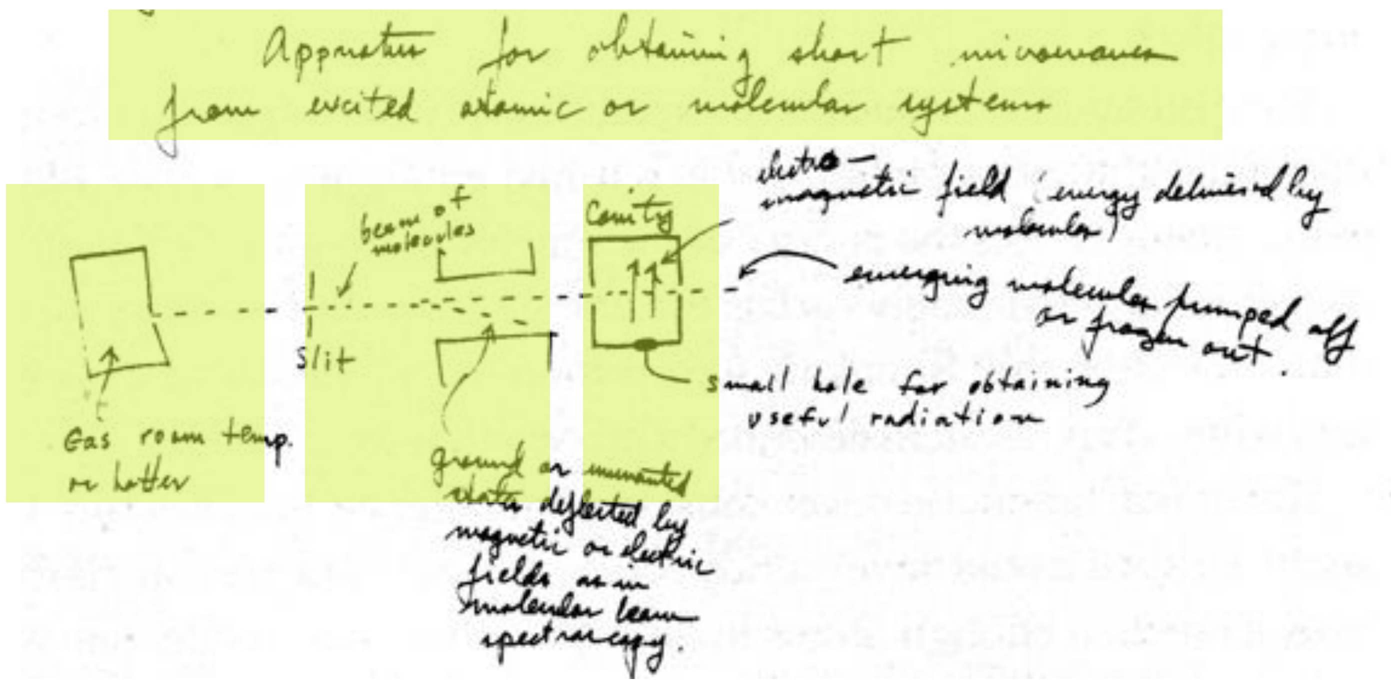
Into the above cavity a stream of molecules flow which may exist in states with energy difference hν. Molecules in the lower one of these states have been deflected away by standard molecular beam techniques. Molecules in still other states may exist in the beam but are not of much importance. Molecules in the wanted excited state radiate slowly at first by "spontaneous" emission, but if energy is emitted into cavity, and the cavity is fairly "high Q", the random thermal field in the cavity will have been increased slightly, thus making emission from subsequent molecules more probable. The field is gradually built up as more emissions are induced until about all excited molecules entering the cavity make transitions and molecules emerge from cavity half in ground state + half in excited state. Oscillations will occur if losses in cavity are less than the power delivered by excited molecules. Rough calculations show that power of approx. 10^{-6} watts might be obtained at frequency of 5×10^{11} cycles/sec or ½ cm. wavelength. This system has the advantage that it should work at much shorter wavelengths if sufficiently lossless cavity can be found and cavity may be quite large compared to wavelength. Frequency will be precisely determined by molecular resonant frequency, and may be varied by Zeeman or Stark effect, or somewhat by tuning cavity. Radiation would be essentially monochromatic since all induced transitions would be exactly in phase with initial radiation.

This general scheme occurred to me on April 26, 1951 in Franklin Park, Washington D.C. It was explained to A. L. Schawlow the same day and on May 1 to A. Nethercot and N. Kroll. Nethercot discussed this scheme at a meeting in Illinois May 2 or May 3.

Chas. H. Townes May 11, 1951.

Read and understood by me on Feb. 28, 1952. This method was explained to me Apr. 26, 1951
A. L. Schawlow

Labbook Townesa



Apparatus for obtaining short microwaves
from excited atomic or molecular system

Gas [in] room temp.
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Ground or unwanted
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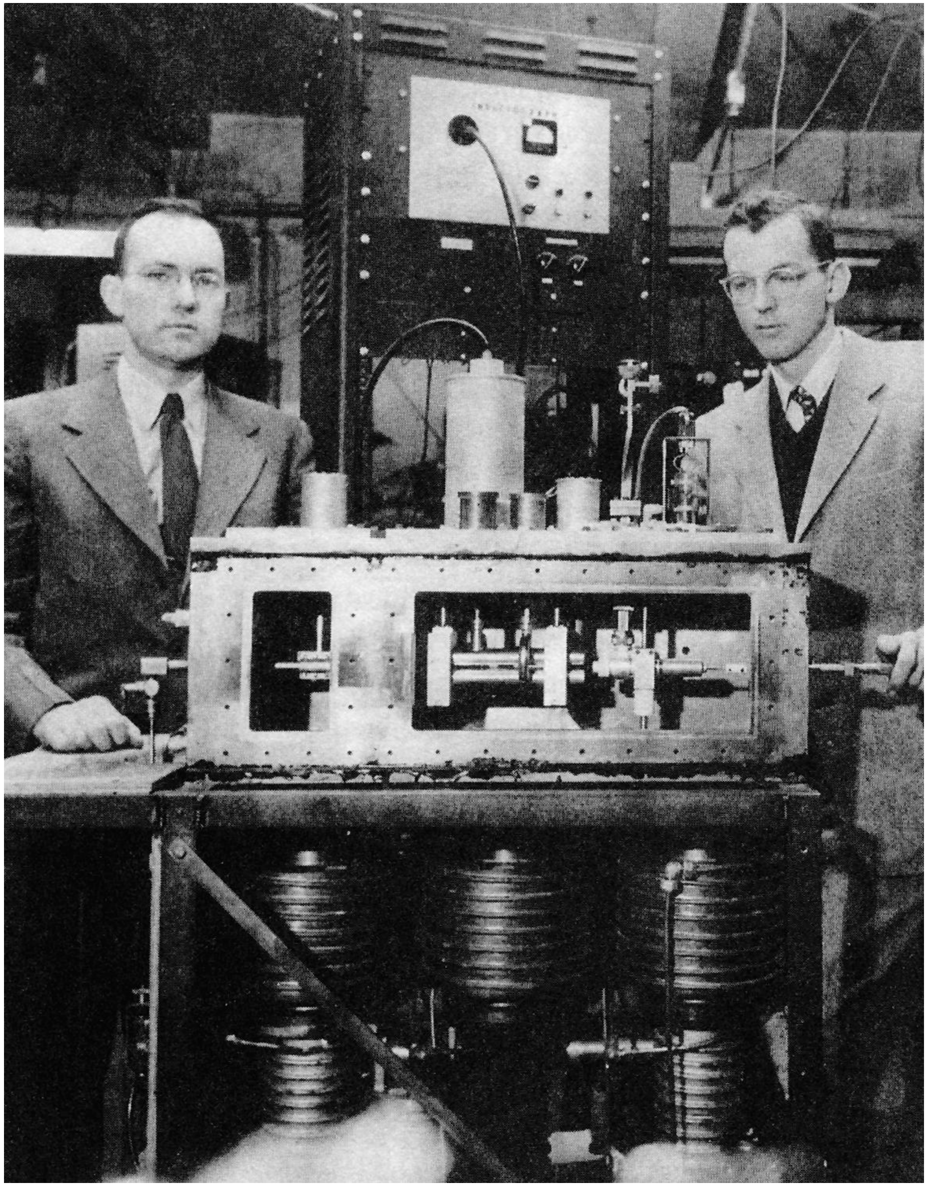
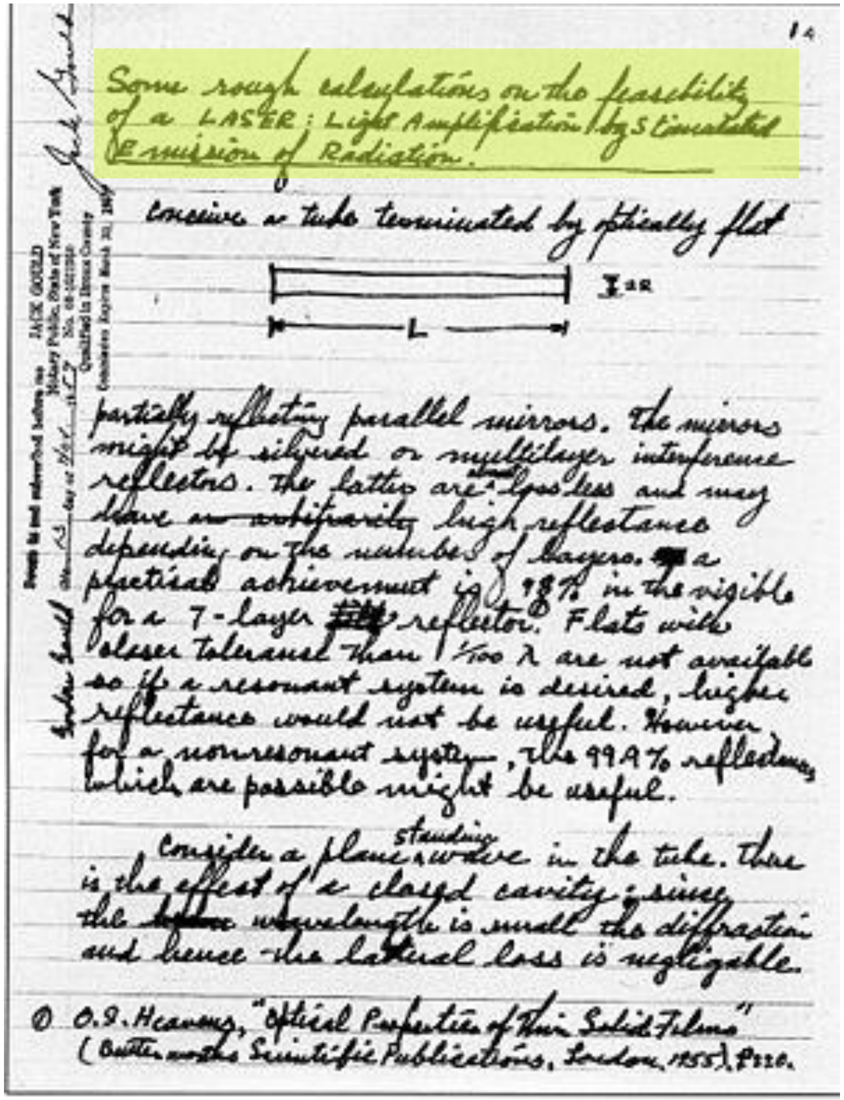
Laser – początki



James Gordon i Charles Townes przy drugim działającym maserze wykorzystującym wiązkę cząsteczek amoniaku do wzmocnienia mikrofal o długości fali 1,25 cm

LASER po raz pierwszy – *Gordon Gould (TRG)*


Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation.

Conceive a tube terminated by optically flat

partially reflecting parallel mirrors. The mirrors might be silvered or multilayer interference reflectors. The latter are almost lossless and may have an arbitrarily high reflectance depending on the number of layers. A practical achievement is 98% in the visible for a 7-layer reflector.① Flats with closer tolerance than 1/100 λ are not available so if a resonant system is desired, higher reflectance would not be useful. However for a nonresonant system, the 99.9% reflectors which are possible might be useful.

Consider a plane standing wave in the tube. There is the effect of a closed cavity; since the wavelength is small the diffraction and hence the lateral loss is negligible.

① O.S. Heavens, "Optical Properties of Thin Solid Films" (Butterworths Scientific Publications, London, 1955), p.220.

Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation

Theodore (Ted) Maiman

16 maja 1960
poniedziałek
Hughes Laboratories

Theodore (Ted) Maiman

494 NATURE August 6, 1960 VOL. 187

Stimulated Optical Radiation in Ruby

Schawlow and Townes[1] have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan[2] and Sanders[3] have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å.; the active material used was ruby (chromium in corundum).

A simplified energy-level diagram for triply ionized chromium in this crystal is shown in Fig. 1. When this material is irradiated with energy at a wave-length of about 5500 Å., chromium ions are excited to the $^4F_2$ state and then quickly lose some of their excitation energy through non-radiative transitions to the ^2E state[4]. This state then slowly decays by spontaneously emitting a sharp doublet the components of which at 300° K. are at 6943 Å. and 6929 Å. (Fig. 2a). Under very intense excitation the population of this metastable state (^2E) can become greater than that of the ground-state; this is the condition for negative temperatures and consequently amplification via stimulated emission.

To demonstrate the above effect a ruby crystal of 1-cm. dimensions coated on two parallel faces with silver was irradiated by a high-power flash lamp;

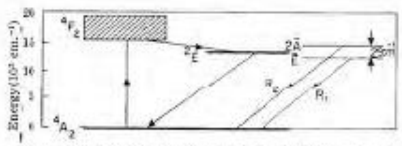


Fig. 1. Energy-level diagram of Cr^{3+} in corundum, showing pertinent processes

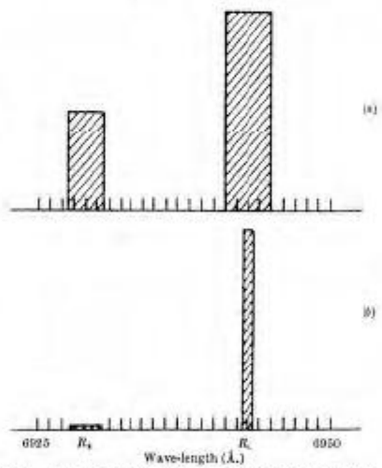


Fig. 2. Emission spectrum of ruby: a, low-power excitation; b, high-power excitation

the emission spectrum obtained under these conditions is shown in Fig. 2b. These results can be explained on the basis that negative temperatures were produced and regenerative amplification ensued. I expect, in principle, a considerably greater (~ 10^4) reduction in line width when mode selection techniques are used[1].

I gratefully acknowledge helpful discussions with G. Birnbaum, R. W. Hellwarth, L. C. Levitt, and R. A. Satten and am indebted to I. J. D'Haenens and C. K. Asawa for technical assistance in obtaining the measurements.

T. H. MAIMAN

Hughes Research Laboratories,
A Division of Hughes Aircraft Co.,
Malibu, California.

[1] Schawlow, A. L., and Townes, C. H., Phys. Rev., 112, 1940 (1958).
[2] Javan, A., Phys. Rev. Letters, 3, 87 (1959).
[3] Sanders, J. H., Phys. Rev. Letters, 3, 86 (1959).
[4] Maiman, T. H., Phys. Rev. Letters, 4, 564 (1960).

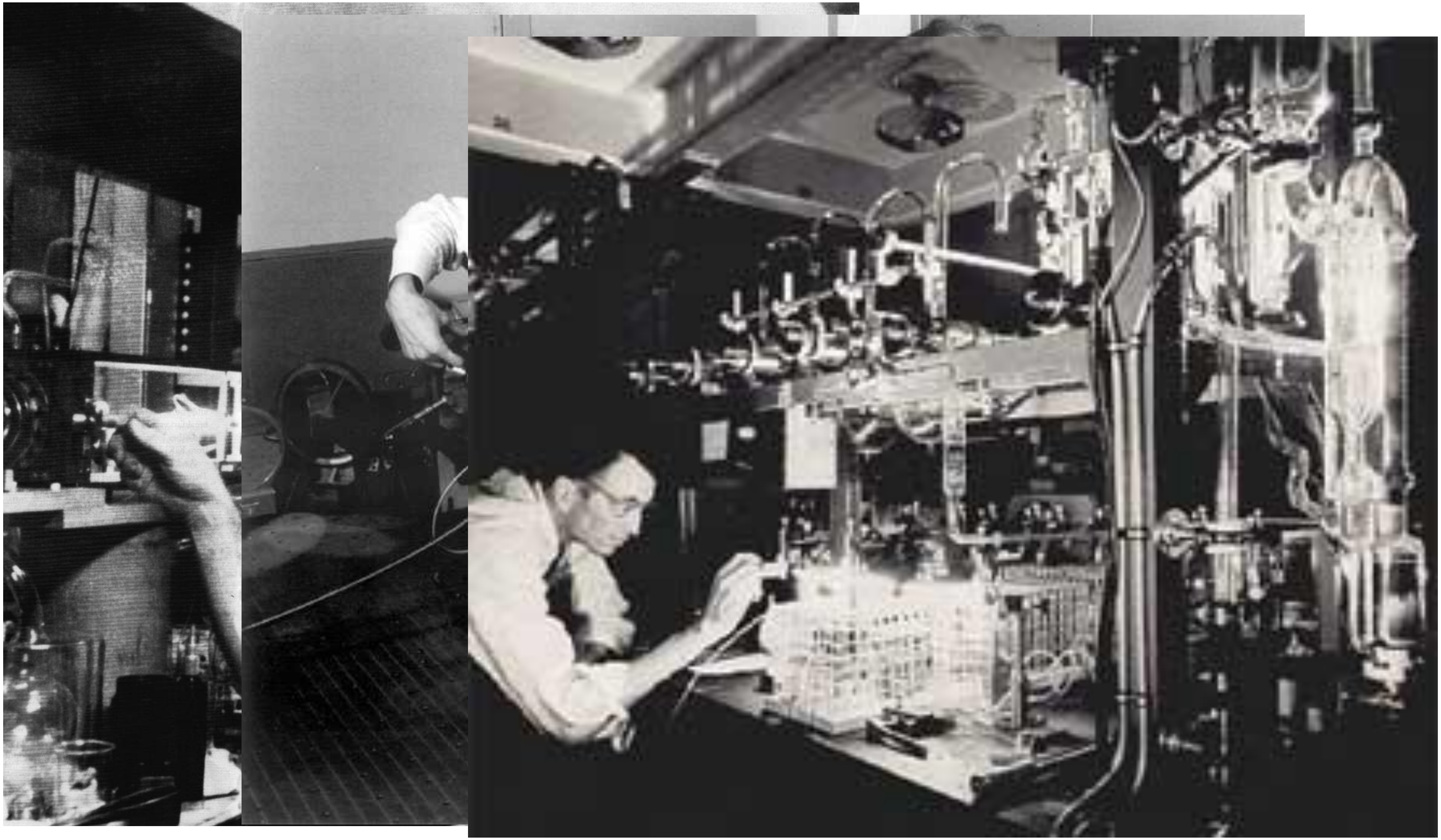
In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at the wave-length of 6943 Å.

Under very intense excitation the population of this metastable state (2E) can become greater that that of the ground-state; this is the condition for the negative temperatures and consequently amplification via stimulated radiation.

Początki

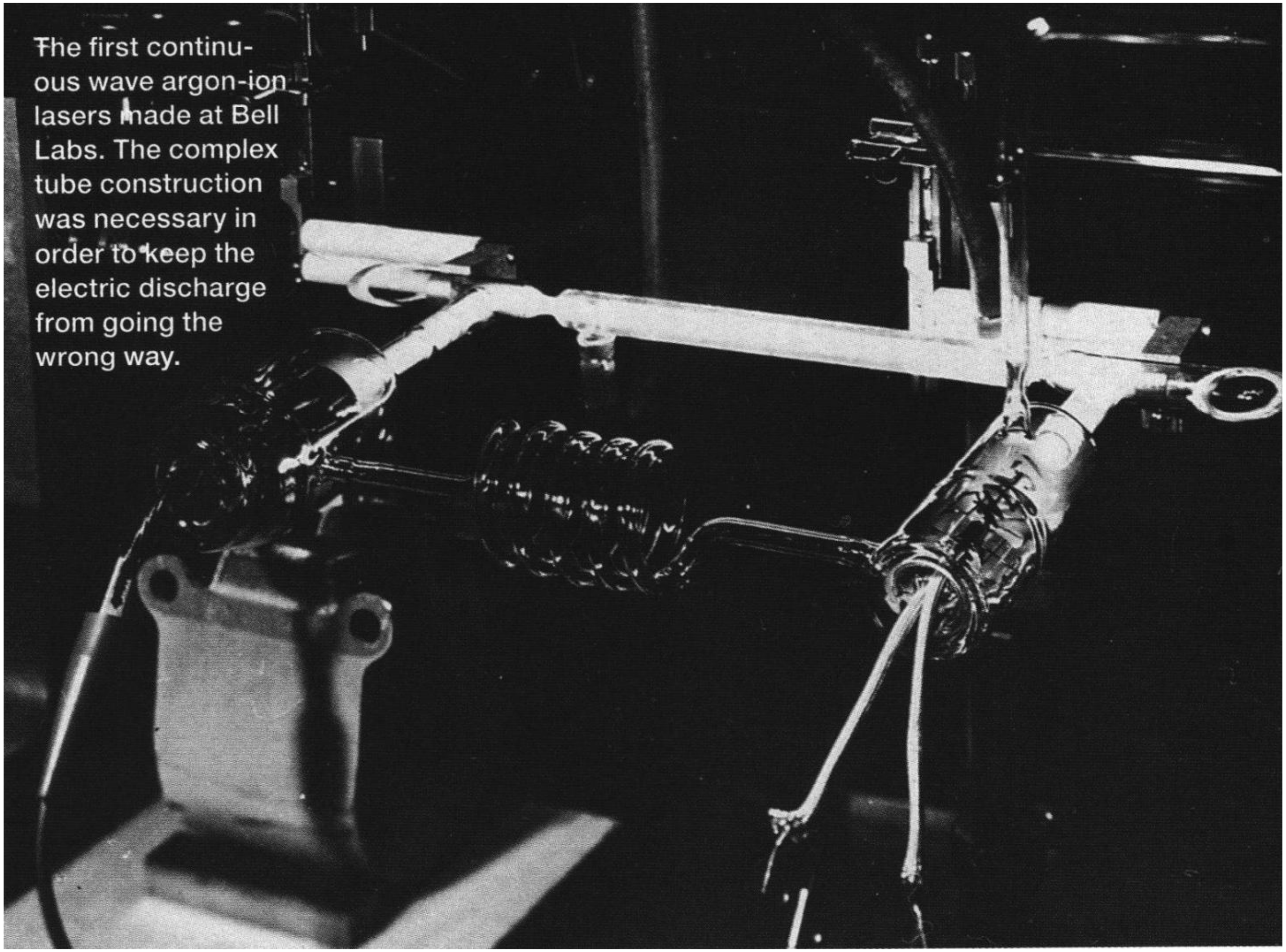
Pierwszy laser po 40 latach - rekonstrukcja

Początki



Pierwszy laser He-Ne, Javan, Benett, Herriott, 1961, Bell Labs

Młodość



Pierwszy laser argonowy, Bell Labs

W Polsce (WAT)

Pierwszy polski laser (He-Ne),
20 sierpnia 1963,
Puzewicz, Dzięciołowski

Wiek dojrzały

półprzewodniki

1962 – pierwszy laser półprzewodnikowy oparty na GaAs (GE, IBM, MIT)

1963 – laser oparty o heterozłącze półprzewodnikowe

1975 – pierwsza komercyjna dioda laserowa pracy ciągłej działająca w temperaturze pokojowej

1979 – VCSEL

1996 – GaN

atomy i światło

1961 – druga harmoniczna

1964 – maser i pomiar promieniowania tła

1967 – separacja izotopów (bromu)

1970 – penseta optyczna

1985 – pułapkowanie i chłodzenie atomów

1995 – BEC

2000 – optyczne grzebienie częstości

medycyna

1961 – pierwsza operacja (siatkówki)

1987 – operacja rogówki

1998 – LASIK

komunikacja

1965 – płyta CD

1968 – pierwszy laser w kosmosie

1970 – pierwsza laserowa latarnia morska

1971 – komercyjny światłowód (Corning)

1974 – kod kreskowy

1977 – telefonia

1982 – fotolitografia

1988 – kabel pod oceanem

1995 – GPS

Nagrody Nobla

1964: Charles H. Townes, Alexander M. Prokhorov i Nicolay G. Basov za "fundamentalne prace z dziedziny elektroniki kwantowej, które doprowadziły do skonstruowania oscylatorów i wzmacniaczy opartych na zasadzie masera-lasera",

1966: Alfred Kastler za "odkrycie i rozwinięcie metod optycznych pozwalających badać rezonanse Hertza w atomach",

1971: Dennis Gabor za "wynalezienie i rozwinięcie holografii" ,

1981: Arthur Schawlow i Nicolaas Bloembergen za "wkład w rozwój spektroskopii laserowej",

1997: Steven Chu, Claude Cohen-Tannoudji i William D. Phillips za "rozwój metod pułapkowania i chłodzenia atomów przy pomocy światła laserowego",

2000: Zhores I. Alferov i Herbert Kroemer za "podstawowe prace w dziedzinie technologii informatycznych i komunikacyjnych" oraz "rozwinięcie heterostruktur do zastosowań w ultraszybkiej optoelektronice",

2001: Eric Cornell, Carl Wieman i Wolfgang Ketterle za "osiągnięcie kondensacji Bosego-Einsteina w gazie",

2005: John L. Hall i Theodor W. Hansch za "wkład w rozwój precyzyjnej spektroskopii laserowej, w tym optycznych grzebieni częstości",

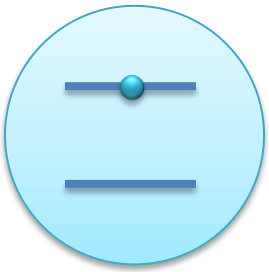
2009: Charles K. Kao, Willard S. Boyle, and George E. Smith "za przełomowe osiągnięcia w technologii przesyłania informacji włóknami światłowodowymi".

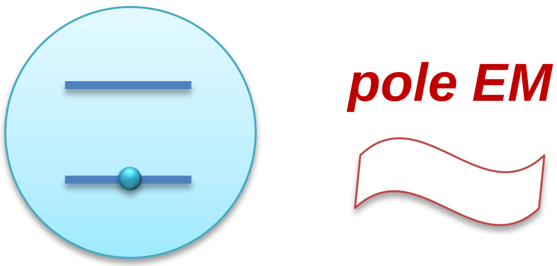
Oddziaływanie foton - atom

założenia:

- jeden atom dwupoziomowy
- wnęka rezonansowa (rezonator) dla światła
- wybieramy 1 mod rezonatora (υ – objętość modu)

- emisja spontaniczna (*spontaneous emission*)





$$\frac{dN_2}{dt} = -\frac{dN_1}{dt} = -A_{21}N_2$$

$$N_2(t) = N_2(0)e^{-A_{21}t} = N_2(0)e^{-t/\tau_{sp}}$$

τ_{sp} - czas spontanicznego zaniku populacji w stanie górnym

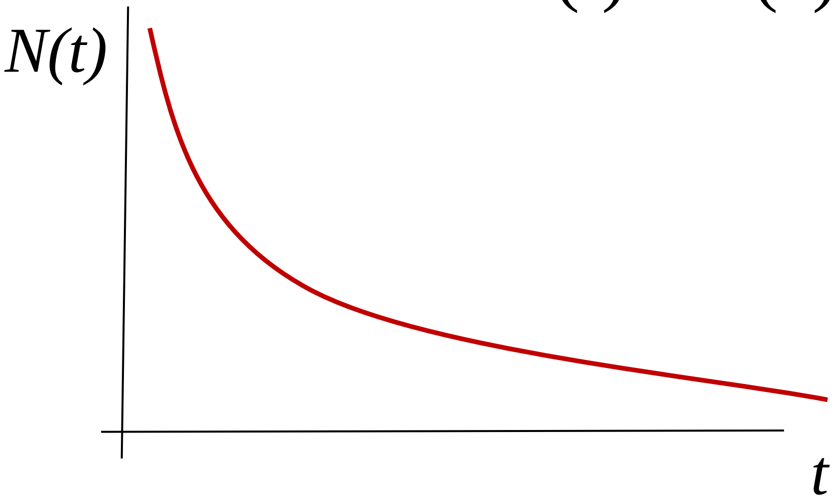
Emisja spontaniczna

dla dużej liczby $N(0)$ atomów początkowo w stanie wzbudzonym

$$-\Delta N = (p_{sp}\Delta t)N$$

$$\frac{dN}{dt} = -p_{sp}N$$

$$N(t) = N(0)e^{-p_{sp}t} = N(0)e^{-t/\tau_{sp}}$$



τ_{sp} - spontaniczny czas zaniku fluorescencji

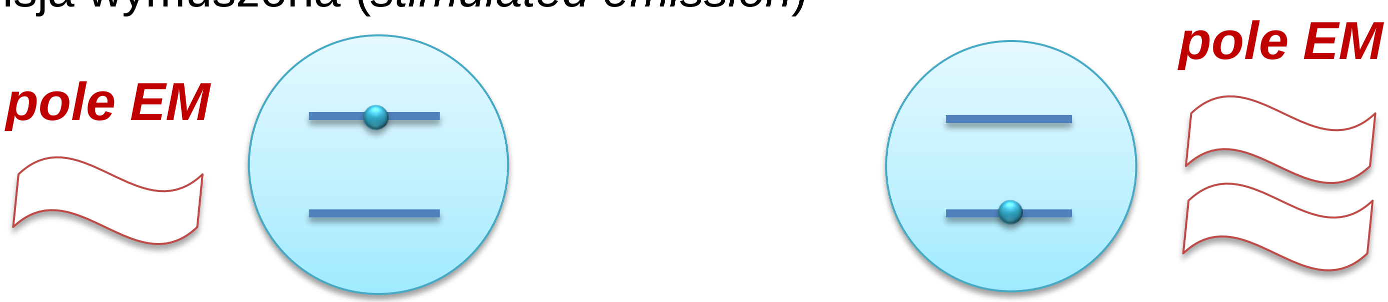
Oddziaływanie światło – atom, pozostałe procesy

- absorpcja (*absorption*)

szybkość absorpcji

$$\frac{dN_2}{dt} = -\frac{dN_1}{dt} = B_{12}u(\omega)N_1$$

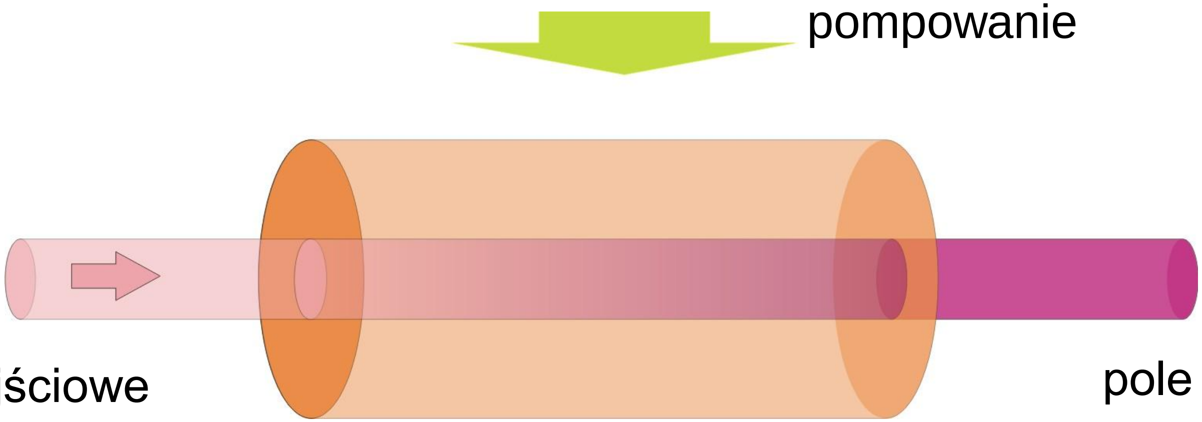
- emisja wymuszona (*stimulated emission*)



szybkość emisji wymuszonej

$$\frac{dN_1}{dt} = -\frac{dN_2}{dt} = B_{21}u(\omega)N_2$$

Wzmocnienie światła



wzmacniacz idealny : $\vec{E}_{out}(t) = G \cdot \vec{E}_{in}(t)$

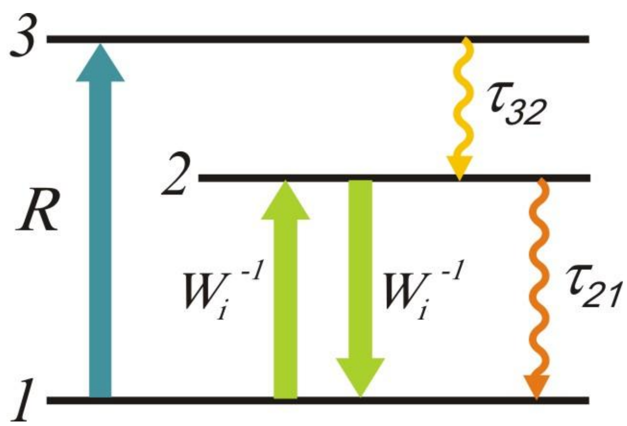
wzmocnienie *G*>1

wzmacniacz rzeczywisty:

wzmocnienie
pasmo
zmiana fazy
szum
nasycenie
pompowanie

Rzeczywiste schematy pompowania

- schemat 3 - poziomowy



$N = N_1 + N_2 + N_3$ (gęstość atomów)

$R_1 = R_2 = R$

$\tau_1 = \infty$ (stan podstawowy)

przybliżenie: $\tau_{32} \simeq 0 \Rightarrow N_3 \simeq 0$

$$\begin{cases} \dfrac{dN_2}{dt} = RN_1 - \dfrac{N_2}{\tau_{21}} - N_2 W_i + N_1 W_i \\ N_1 = N - N_2 \end{cases}$$

$$\Delta N = N_2 - N_1 = 2N_2 - N$$

$\Delta N > 0 \Rightarrow N_2 > \dfrac{N}{2}$ musimy ponad połowę atomów przenieść na poziom 2

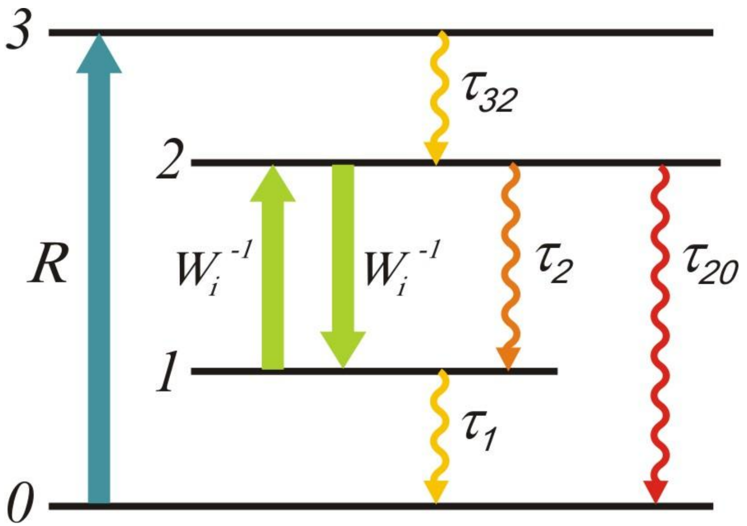
małe $\phi \Rightarrow$ małe $W_i = \phi \cdot \sigma$ $\quad \Delta N_0 = \dfrac{R\tau_{21} - 1}{R\tau_{31} + 1}$ $\quad \Delta N_0 > 0 \Leftrightarrow R > \dfrac{1}{\tau_{21}}$

nienasycona inwersja obsadzeń

duże ϕ $\quad \Delta N = \dfrac{\Delta N_0}{1 + \tau_s W_i}$ $\quad \tau_s = ?$

Rzeczywiste schematy pompowania

- schemat 4 – poziomowy (najlepszy)



$$\begin{cases} \frac{dN_2}{dt} = RN_0 - \frac{N_2}{\tau_2} - \Delta N W_i \\ \frac{dN_1}{dt} = \frac{N_2}{\tau_{21}} - \frac{N_1}{\tau_1} + \Delta N W_i \\ N_0 + N_1 + N_2 = N \end{cases}$$

rozwiązania stacjonarne $\left(\frac{dN_i}{dt} = 0 \right)$:

$\tau_{32} << \tau_2 (N_3 \approx 0)$

- małe ϕ , zaniedbujemy przejścia wymuszone pomiędzy poziomami 1 i 2

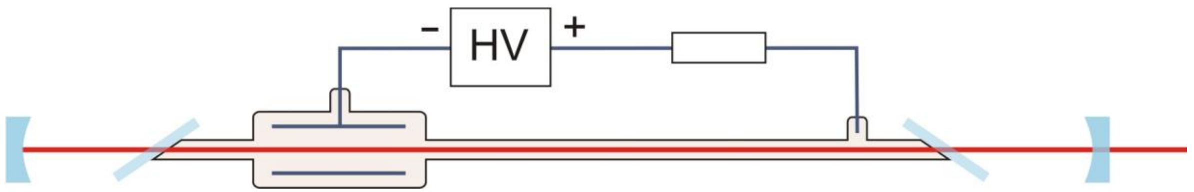
$$\Delta N_0 = R\tau_2 \left(1 - \frac{\tau_1}{\tau_{21}} \right)$$

$$\Delta N_0 > 0 \Leftrightarrow \frac{\tau_1}{\tau_{21}} < 1 \Rightarrow \tau_1 < \tau_{21}$$

$$\Delta N_0 = NR\tau_2 \frac{\left(1 - \frac{\tau_{10}}{\tau_{21}} \right)}{1 + R(\tau_{10} + \tau_{21})}$$

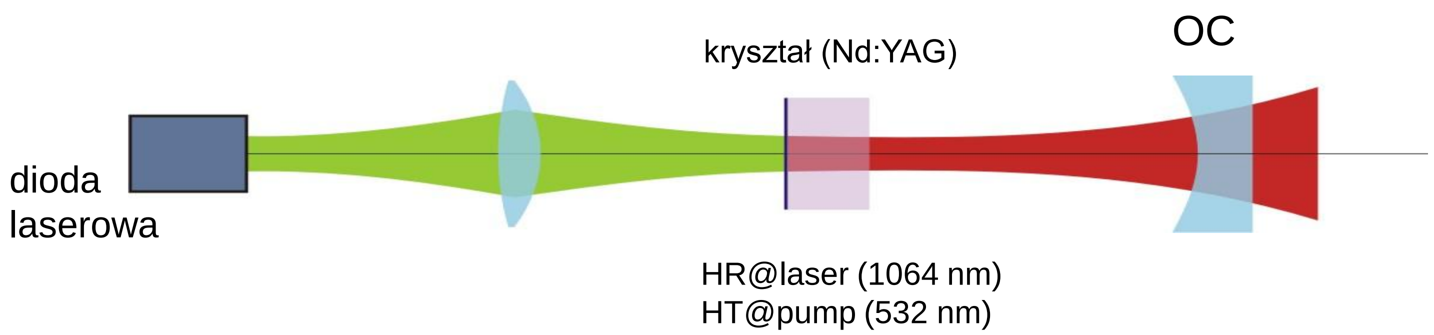
Metody pompowania ośrodków wzmacniających

- **wyładowanie elektryczne w gazie** (He-Ne, Ar, He-Cd, CO_2)



- **lampy błyskowe (Nd:YLF)**

- **wiązka innego lasera (Nd:YAG, włókna)**



- **reakcja chemiczna (HF)**

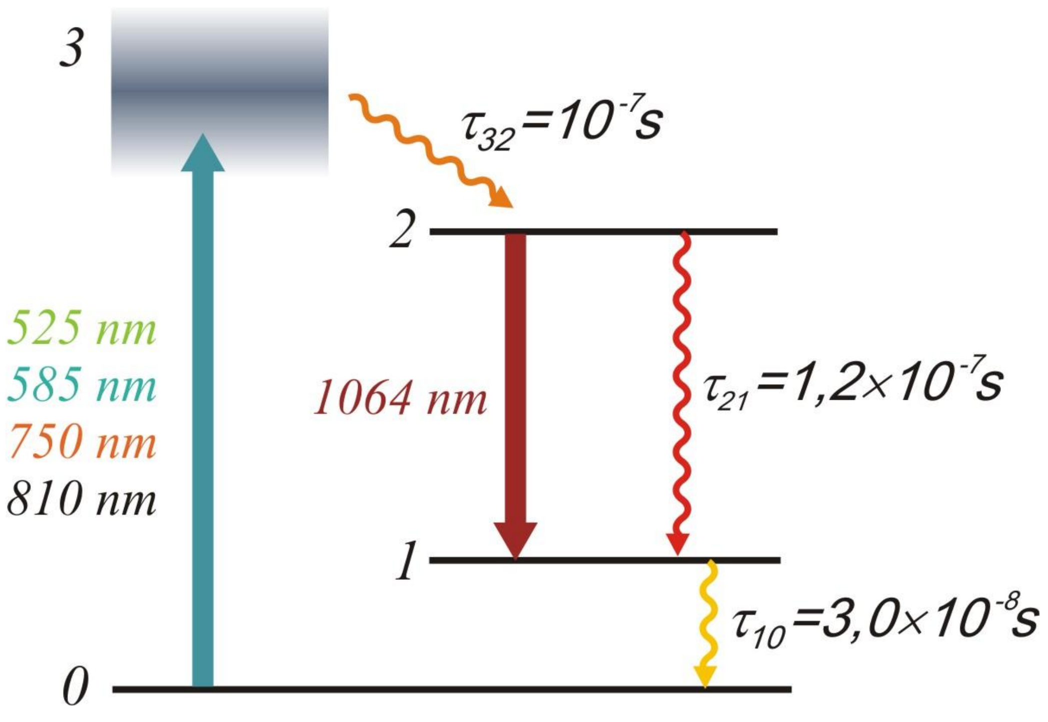
Wybrane ośrodki wzmacniające

J – poszerzenie jednorodne
NJ – poszerzenie niejednorodne

	$\lambda_0[\mu m]$	$\sigma_0[cm^2]$	τ_{sp}	$\Delta\nu$	n
He-Ne	0.6328	1×10^{-13}	$0.7\mu s$	$1.5GHz$ NJ	1
Rubin $Cr^{3+}:Al_2O_3$	0.6943	2×10^{-20}	$3ms$	$60GHz$ J	1.76
Nd^{3+}:YAG ($Y_3Al_2O_{12}$)	1.064	4×10^{-19}	$1.2ms$	$120GHz$ J	1.82
Nd^{3+}:szkło	1.06	3×10^{-20}	$0.3ms$	$3THz$ NJ	1.5
Er^{3+}:włókno	1.55	6×10^{-21}	$10ms$	$4THz$ J/NJ	1.46
RhGG (barwnik)	0.56-0.64	2×10^{-16}	$3ns$	$5THz$ J/NJ	1.33
Ti:Al_2O_3 szafir	0.66-1.18	3×10^{-19}	$3.2\mu s$	$100THz$ J	1.76
CO_2	10.6	3×10^{-18}	2.9	$60MHz$ J	1
Ar^+	0.515	3×10^{-12}	$10ns$	$3.5GHz$ J	1

Przykład rzeczywistego schematu pompowania – Nd: YAG

Nd^{3+} : $Y_3Al_5O_{12}$ 4 - poziomowy



poszerzenie jednorodne 120 GHz

praca ciągła (CW) bądź impulsowa

pompowanie: lampy błyskowe, lasery diodowe

Dynamika lasera – przegląd

Przełączanie wzmocnienia – *gain switching*

Przełączanie dobroci wnęki – *cavity dumping*

Przełączanie dobroci wnęki – *Q-switching*

Synchronizacja modów podłużnych – *mode locking*