Outline

• A few personal notes

• Harmonic generation

• Optical parametric oscillators

• Highly nonlinear optics

This is not an academic review by any means!
Interactions between Light Waves in a Nonlinear Dielectric

J. A. Armstrong, N. Bloembergen, J. Dicuing,† and P. S. Pershan
Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts
(Received April 16, 1962)
First brush with nonlinear optics (1965)
Physics meets the Beatles

ELECTRO-OPTIC LIGHT MODULATOR

MODEL JX-2A

GENERAL
The Baird-Atomic electro-optic light modulator (EOLM) provides a practical answer to problems requiring light pulses in the nano-second region, as well as to those which depend upon the modulation of a light beam at frequencies from dc through the video region. Numerous applications have been found in the fields of communications, polarimetry, densitometry, photography, photometry, interferometry, measurement of semiconductor parameters and laser modulation.

Figure 1. JX-2A EOLM
It was from this office that Nico Bloembergen generated the ideas for the 3 Level Maser and Non-Linear Optics and also supervised the experiments.
Ruby lasers enabled demonstrations of NLO

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 \(4^2F_3\) state and then quickly lose some of their excitation energy through non-radiative transitions to the \(4^2E\) state. This state then slowly decays by spontaneously emitting a sharp doublet of 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 \(4^2E\) 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; 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 \((-10^9\) reduction in line width when mode selection techniques are used\(^4\).

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

T. H. MAIDMAN

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


METALLURGY

A Simple Method of investigating the Creep of Metals under Simple Shear

DR. K. H. JOLLIFFE and I\(^1\) have investigated the creep of metals under simple shear by the use of a disk of the metal in question, in which is cut a concentric circular annulus, the metal external to the annulus being securely gripped, while that internal to the annulus is subjected to a constant torque. We
Pictures of first ruby laser at Hughes
My pursuits in linear optics bore fruit in 1982.

4 JUNE 82

(Ti:Al₂O₃ LASER)

(f = 25 cm)

(FP DYE LASER
Coomarin 504)

M₁, M₂ He-Ne MIRRORS

Ti:Al₂O₃ CRYSTAL (SAME SAMPLE AS ON P. 115)

LASING OBSERVED VISUALLY
Materials technology does matter!
• A few personal notes

• Harmonic generation

• Optical parametric oscillators

• Highly nonlinear optics
The parade of nonlinear crystals

- KDP ($\text{KH}_2\text{PO}_4$) family (inherited from acoustic transducers)
- Niobates - $\text{LiNbO}_3$, $\text{KNbO}_3$, $\text{Ba}_2\text{NaNb}_5\text{O}_{12}$
- KTP ($\text{KTiOPO}_4$) family
- Borates - $\text{BBO}$ ($\beta\text{-BaB}_2\text{O}_4$), $\text{LBO}$ ($\text{LiB}_3\text{O}_5$), $\text{BiBO}$ ($\text{BiB}_3\text{O}_6$)
- Quasi phase-matched
  - Periodically poled (PPLN, PPSLT, PPKTP)
  - Orientation patterned (OP-GaAs)
Not always this easy to grow these big crystals

KDP (thanks to Cleveland Crystals, LLNL)
NIF is 50-100 times more energetic than any other laser

- 192 Beams
- Frequency tripled Nd glass
- Energy 1.8 MJ
- Power 500 TW
- Wavelength 351 nm
Key to practical laser fusion?

- Pair of type I or type II doublers
- CPP plate (removable)
- Pair of type II triplers

Beam direction

- $2\omega$
- $3\omega$
- >96% deuterated KD*P

He gas flow between each plate and between crystal surfaces is required to maintain crystal temperature gradients to specifications (TBD)

Gap between crystal pairs is small (1-mm) to prevent “harmonic interference” and improve cooling efficiency

Type I input

Or

Type II input

35.3 deg
CONTINUOUS 0.532-μ SOLID-STATE SOURCE USING Ba₂NaNb₅O₁₅

Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey 07974
(Received 11 March 1968)

A continuous 0.532-μ solid-state source utilizing the nonlinear material Ba₂NaNb₅O₁₅ inside the cavity of a 1.064-μ YAIG:Nd laser has generated 1.1 W of coherent green power. This represents 100% conversion to the green of the available infrared radiation from the YAIG:Nd laser utilized.

CONTINUOUS OPTICAL PARAMETRIC OSCILLATION IN Ba₂NaNb₅O₁₅

Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey 07974
(Received 21 February 1968)

A tunable, optical parametric oscillator using a continuous pump is reported. The threshold was measured to be 45 mW of multimode power at 0.532 μ. The efficiency was found to be 1% with 300 mW of pump power.
KTP (and isomorphs)

- **Features**
  - High damage threshold
  - CPM for Nd SHG has large acceptance angle
  - Relatively temperature insensitive
  - Large apertures available for high-energy systems
  - Isomorphs available for special applications

- **Bugs**
  - Induced absorption limits average power in green
  - High n2, self focusing
  - Damage centers (gray tracking) form in bulk with green generation
  - Explodes when absorbing energy too quickly
• **Features**
  – Large birefringence, allowing phase-matching over a wide range
  – Moderate nonlinearity
  – High damage threshold
  – Good UV transparency
  – Temperature insensitivity

• **Bugs**
  – Large birefringence, leading to large walkoff and small angular acceptance
  – Tendency to form damage centers with UV generation
BBO extends operation into the UV

Transmission of 8 mm Thick BBO
Uncoated & Protectively Coated Crystals

Transmission

wavelength - microns
Phase-matching angle vs. wavelength

**Diagram:**

- **Title:** TYPE I SHG
- **x-axis:** FUNDAMENTAL WAVELENGTH (nm)
- **y-axis:** INTERNAL PHASE-MATCHING ANGLE (deg.)
- **Graph:**
  - BBO
  - KDP
  - LBO
- **Notation:** d = 0
Ultraviolet generation with passively $Q$-switched microchip lasers

J.J. Zayhowski

Lincoln Laboratory, Massachusetts Institute of Technology, 244 Wood Street, Lexington, Massachusetts 02173-9108

Received November 7, 1995

First, second, third, fourth, and fifth harmonics of the output of a fiber-pumped passively $Q$-switched Nd:YAG microchip laser have been obtained at pulse energies of 8.0, 3.5, 0.3, 0.7, and 0.01 $\mu$J, respectively, in an optical head occupying a volume of less than 3 cm$^3$. This compact, economical all-solid-state source provides coherent subnanosecond multikilowatt infrared, visible, and ultraviolet pulses at repetition rates in excess of 10 kHz. © 1996 Optical Society of America
Bad things happen in the UV

Conduction band

ESA

Pump

Laser

Induced color center

N-photon absorption

Dielectric breakdown

Valence band

Direct lasers

Harmonic generation
Coping with bad things
Walk-off in birefringent phase-matching
Theory shows low walk-off focusing is better.
Results with BBO 262-nm generation

Low-walkoff
3 W maximum power

High-walkoff
5.3 W maximum power
• **Features**
  – Very high damage threshold
  – Ability to operate with NCPM
  – Excellent UV transparency
  – Negligible bulk optical absorption
  – No bulk damage ever observed

• **Bugs**
  – Tricky to grow
  – Funky thermal expansion makes coating difficult
  – Not enough birefringence to generate 4\(^{th}\) harmonic
Chen (on the right) credited with inventing LBO at Fujian (who is that other guy?)
LBO can be temperature tuned into NCPM
LBO NCPM SHG conversion approaches 70%

Theory for 1.8-cm crystal

Data points

Note: Intensity is peak in space and time
Average spatial intensity is half the value shown
LBO-based systems can generate multi-100-W powers

The new Mamba™ Green from Coherent Inc. is a frequency doubled, diode-pumped solid-state laser that offers an exceptional combination of high output power, outstanding reliability and low cost of ownership for a wide range of materials processing tasks.

The Mamba Green delivers over 325 Watts of output at 532 nm (at 10 kHz), yet its integrated doubling crystal shifter and field replaceable gain modules provide an expected operating lifetime of over 25,000 hours.
Goodbye (and good riddance) to argon-ion lasers

Coherent Verdi
(up to 18 W cw)

Spectra-Physics Millenia
(up to 15 W cw)

Finally delivers the promise of cw green from 1968
• A few personal notes
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Time reversal of interactions is allowed

Nonlinear interaction

\[ \omega_3 = \omega_1 + \omega_2 \]

\[ \omega_3 = \omega_1 + \omega_2 \]
BBO OPO widely used in research lasers

Type I BBO OPO

Wavelength, nm

Phase matching angle

532 nm
355 nm
266 nm
Spectra-Physics OPO product
KTA OPO tuning curves, 1053-nm pump

Angle (deg.)

Wavelength (um)

- Signal, x-cut
- Idler, x-cut
- Signal, y-cut
- Idler, y-cut
OPO resonator designs

STANDING-WAVE

- M1
- 20 mm KTP
- HT pump
- HR signal
- PR signal
- HR pump
- Pump feedback

STANDING-WAVE

- 450 mJ, 10 Hz
- 41% conversion
- Limits: M1 damage
- Pump feedback

RING

- signal
- TIR prism
- 240 mJ, 30 Hz
- 34% conversion
- No feedback
- No damage at full power

RING

- 4, 10-mm KTP
Photo and schematic of KTP ring OPO
Highest-energy OPO, NCPM KTP

4.5 W average power
Plot of KTP and KTA IR transmission

- T = 75% @ 3297nm
- T = 23% @ 3297nm

Wavelength (nm)

%T

KTA 2cm
KTP 2cm
High-average-power eyesafe OPO uses KTA

Biological standoff detection system used high-power KTA OPO
Lithium Niobate

- **Features**
  - Large nonlinearity
  - Large crystal sizes possible

- **Bugs**
  - Color centers form with visible light generation, destroying phase-matching
  - Relatively low surface damage threshold
  - Surface acts as dust magnet due to pyroelectricity

- Rescued by QPM for OPO applications

3” diameter stoichiometric crystals
Quasi-phase-matched materials operate by periodically changing sign of nonlinearity

Periodic reversal possible in ferro-electrics
Marty Fejer (on the left) led development of PPLN. Who is the other guy?
PPLN material (HC Photonics)

Standard Lengths* 10, 20, 30, 40 and 50 + 0.05 mm
Thickness 0.5 / 1.0 mm(+ 0.05 mm) typical
Width* 5 mm (+ 0.05 mm) typical
Single grating period > 4 mm
Multi-grating periods 6.5 ~32 mm
Damage Threshold 300 MW/cm² (10ns, 1064nm)
QPM of PPLN OPO allows mid-IR generation

![Graph showing Signal/Idler Wavelengths vs Grating Period](image)

- $\lambda_p = 1064 \text{ nm}$
VIPER system protects aircraft against heat-seeking missiles (MANPADs)
In order to display a full range of colors, electronic displays that project images on a screen must combine red, green and blue light.

Conventional projectors with lamps as light sources take the white light from the lamp and separate out the red, green and blue colors with filters.

Lasers can be used as light sources, and in prior systems three lasers were needed for each color.
High-power RGB source uses LBO in all nonlinear stages

Pump Laser → SHG → OPO → SHG

1047 nm → 523 nm → 898 nm → 449 nm

1256 nm → 628 nm

Blue, Green, Red
A temperature-tuned NCPM LBO OPO is the key element in the system.

523.5-nm pump
First projection attempts lacked color balance
Salem, N.H. -- Laser Light Engines (LLE), a Salem-based developer of laser illumination technology for high-brightness digital projection, announced it has raised $9 million in venture funding, with an additional $6 million anticipated from new investors, bringing the company’s total new funding to $15 million. Founded in 2008, LLE manufactures laser-driven color modules and illumination engines for high-brightness performance projection, signage and lighting applications. The company said the new investment funds will be used to support product rollouts, and strengthen its engineering, sales and manufacturing operations. LLE has now raised $27 million in private funding since its founding.
http://www.laserlightengines.com
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Kerr-lens modelocking (KLM) provides a fast switch to enable femtosecond generation.
Femtosecond OPOs based on Ti:sapphire

Tunable, high-repetition-rate, femtosecond pulse generation in the ultraviolet
M. Ghotbi, A. Esteban-Martin, and M. Ebrahim-Zadeh,*

ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels, Barcelona, Spain

Institucio Catalana de Recerca i Estudis Avancats, Passeig Lluis Companys 23, Barcelona 08010, Spain

*Corresponding author: majid.ebrahim@icfo.es
Fig. 1. Interferometric autocorrelation of a self-starting KLM pulse compared with an ideal 6.5-fs pulse at 750 nm.
Microstructured fiber
- dispersion zero at ~800 nm
- pulses do not spread
- continuum generation via self-phase modulation
• How can we control the absolute frequencies (and hence the group-phase velocities)? *Self-referencing*

![Diagram of spectrum showing fundamental and second harmonic spectra with beat frequency at overlap = \( \delta \)].

Beat frequency at overlap = \( \delta \)


D. J. Jones et al, Science 288 p 635 28 April 2000
Hansch and Hall win Nobel Prize for Optical Combs

Stockholm
December 10, 2005
Photonic crystal fiber and microchip laser enable low-cost supercontinuum source

The supercontinuum source shown is built from a NL-1040 PCF pumped by a nanosecond 1064 nm microchip laser.

Chirped pulse amplification (CPA) avoids NL effects.

1985 (G.Mourou & D.Strikland)
This type of propagation is called filamentation or self-guided propagation. Filamentation of femtosecond laser pulses was shown to occur over more than 50 m in Laboratoire d’Optique Appliquee, (see Fig. 1) and then over several hundreds of meters. Experiments in Spring 2003 at Ecole Polytechnique have revealed an horizontal filamentation over a distance larger than 2 km. Experiments of vertical propagation suggest even larger filamentation distances.
Mechanism for filament formation in air

Kerr effect focuses
\[ \Delta n = n_2 I \]

Ionization defocuses
\[ \Delta n = -\frac{N_e(I)}{2N_{\text{crit}}} \]
Photograph of Ti:sapphire-generated filament
Attosecond pulses, high-harmonic generation
CPA pushes to a Zettawatt (courtesy Mourou)