35 Years of Quasi-Phasematched Nonlinear Optics

M. M. Fejer
E. L. Ginzton Laboratory
Stanford University

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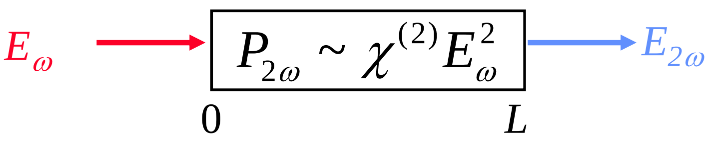
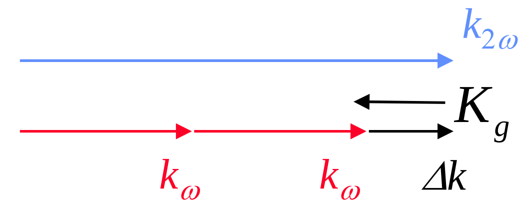
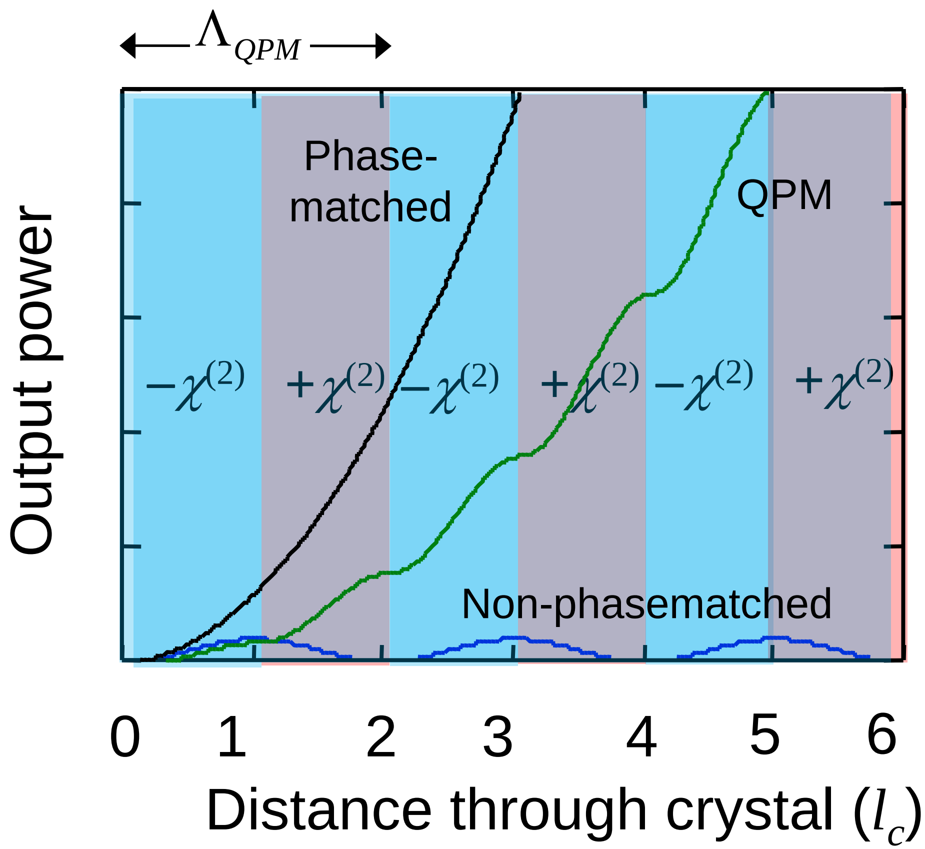
Quasi-phasematching (QPM)







- Dispersion $(\Delta k \neq 0)$ prevents monotonic growth of $E_{2\omega}$
- QPM cancels this effect:

$$\chi^{(2)}(z) = \chi_{eff}^{(2)} e^{iK_g z}$$

- QPM-period ($K_g = 2\pi / \Lambda_{QPM}$) determines which wavelengths can interact.

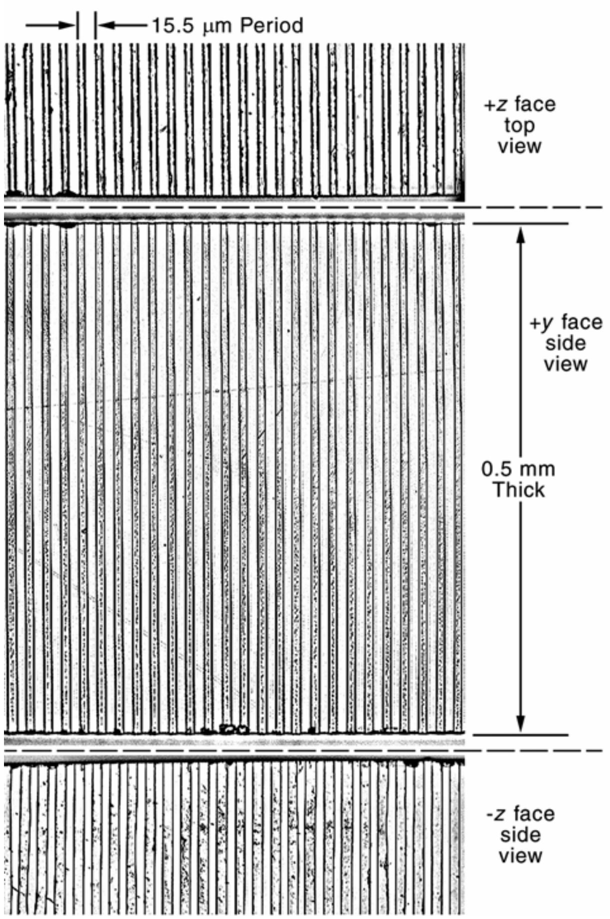
$$\boxed{\Lambda_{QPM} = \frac{\lambda}{2(n_{2\omega} - n_\omega)}}$$

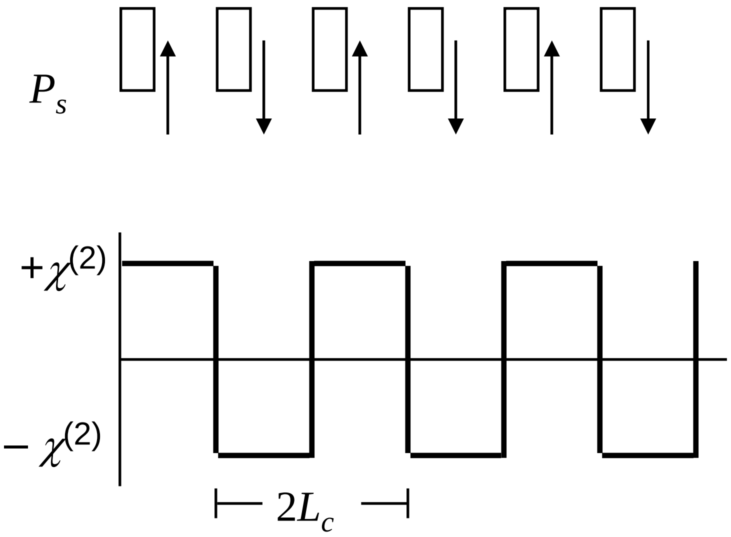
typically 2 – 20 µm

Microstructured Materials Essential for QPM

Ferroelectrics

Large Aspect Ratio Structures
Volume patterning by surface lithography





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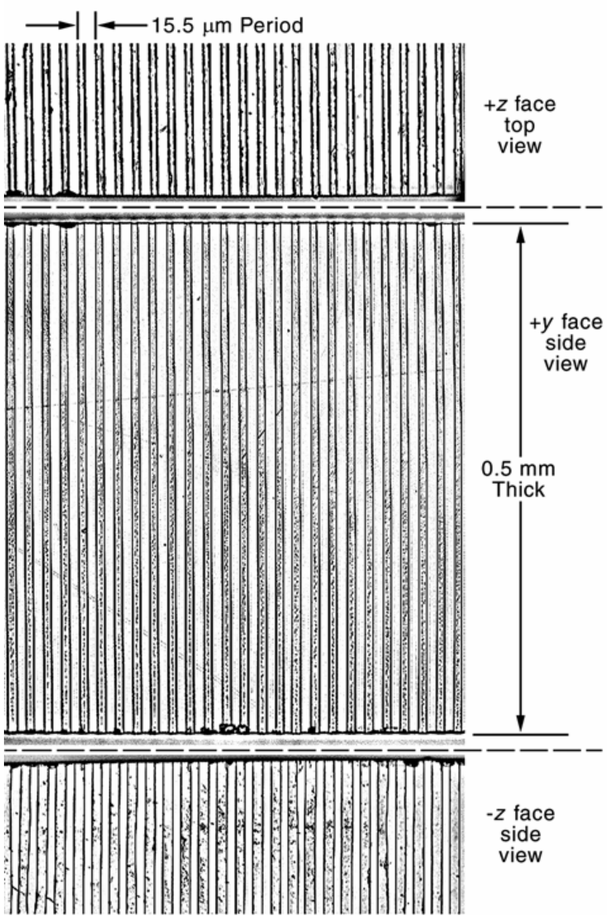
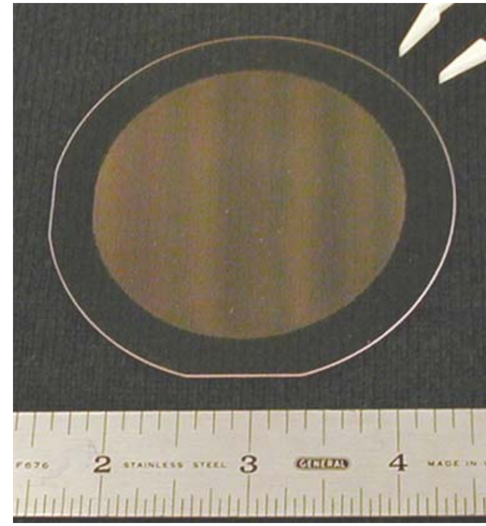
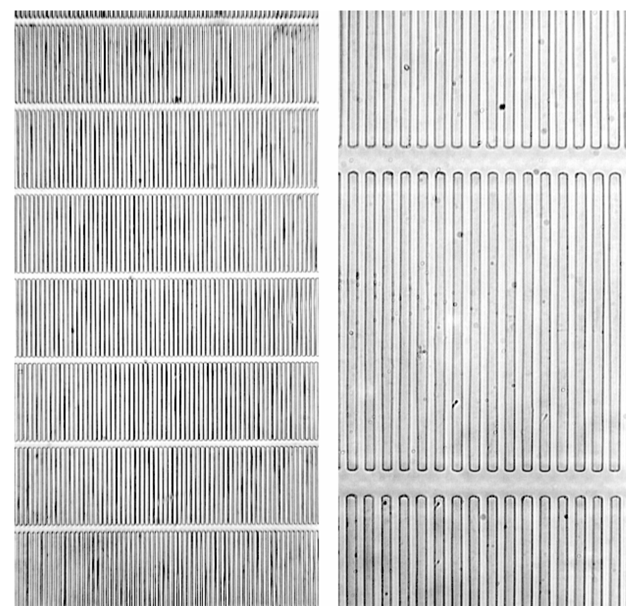


Large Areas
Scalable production



$LiNbO_3$ (PPLN)
$LiTaO_3$ (PPLT)
KTP (PPKTP)

Complex Patterns
Enhanced functionality



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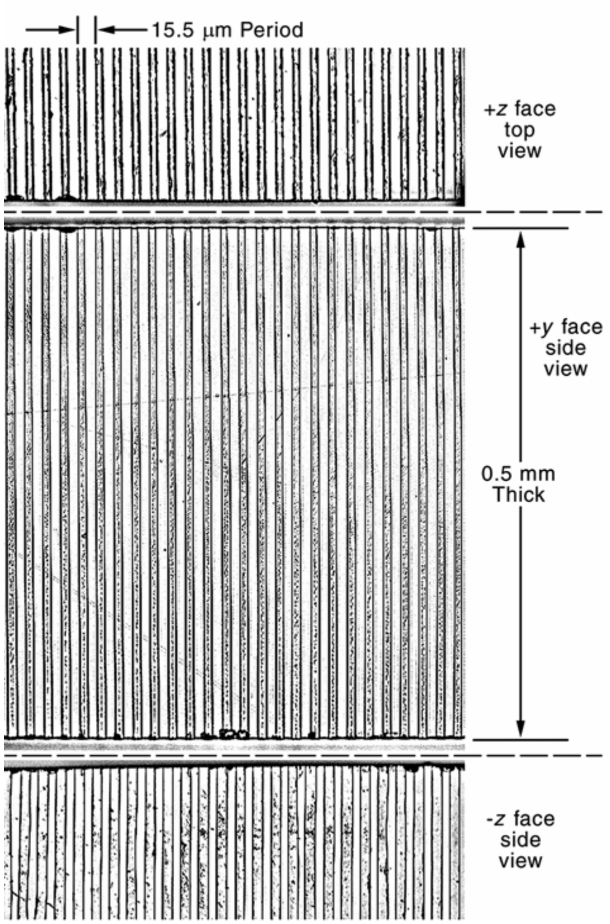

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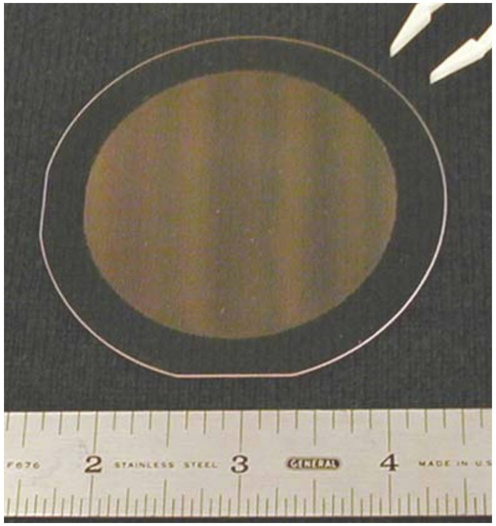

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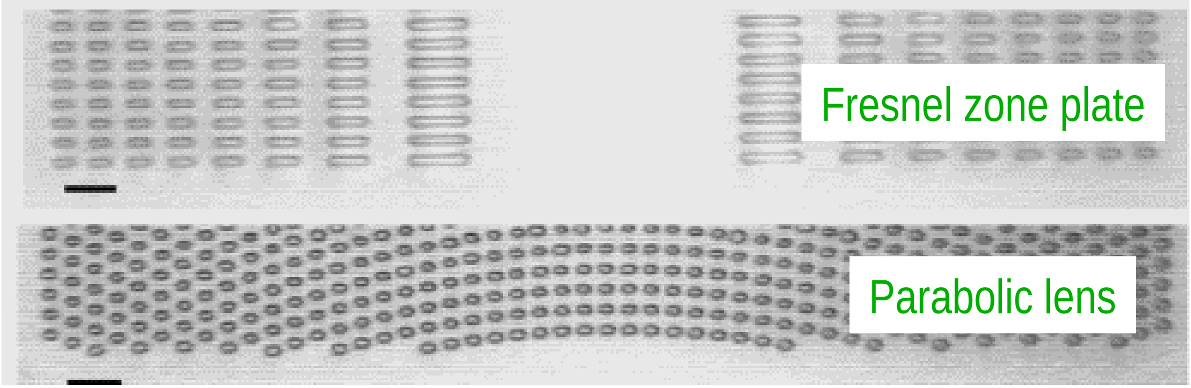
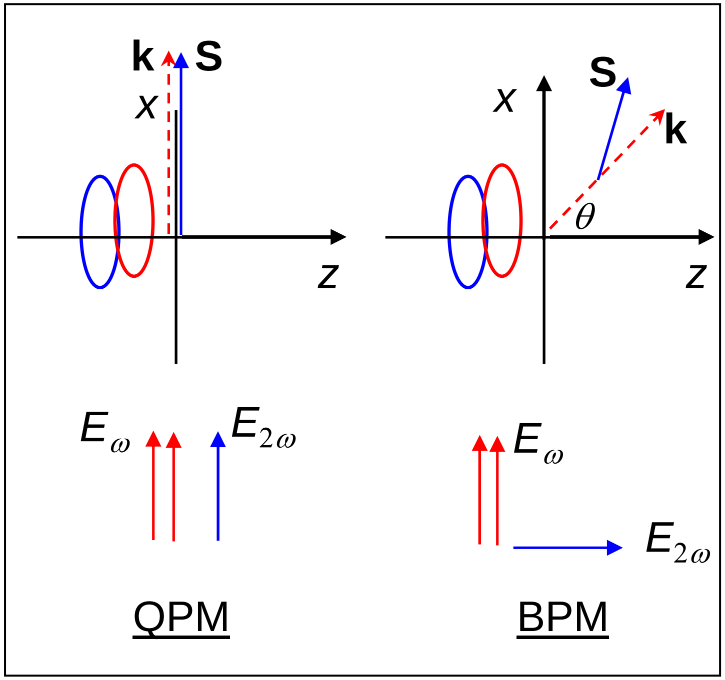


Advantages of QPM

Eliminates dependence on birefringence for phasematching

- Any interaction within transparency range
  - even in non-birefringent materials (GaAs)
- Noncritical phasematching
  - eliminates Poynting vector walkoff
  - especially important for OPOs
- Any desired polarizations
  - use large diagonal nonlinear coefficients
  - for $LiNbO_3$: $d_{33}/d_{31} = 7$
- *Aperiodic gratings*
  - shape temporal, spatial, spectral response



- One material can be tailored for many applications
  - base technology on readily available commodity material

Generic Nonlinear Material
using patternable media
for micron scale features

Fejer, Magel, Jundt, Byer, *IEEE-JQE* **28**, 2631 (1992)

Many Applications for Engineerable Materials

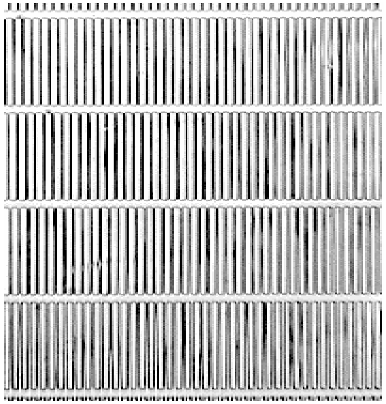
Efficient CW Interactions

large nonlinear susceptibility $\chi^{(2)}$

20 watt CW SHG
532 nm
50% efficiency

Multigratings for broadly tuning OPOs

each grating a different wavelength



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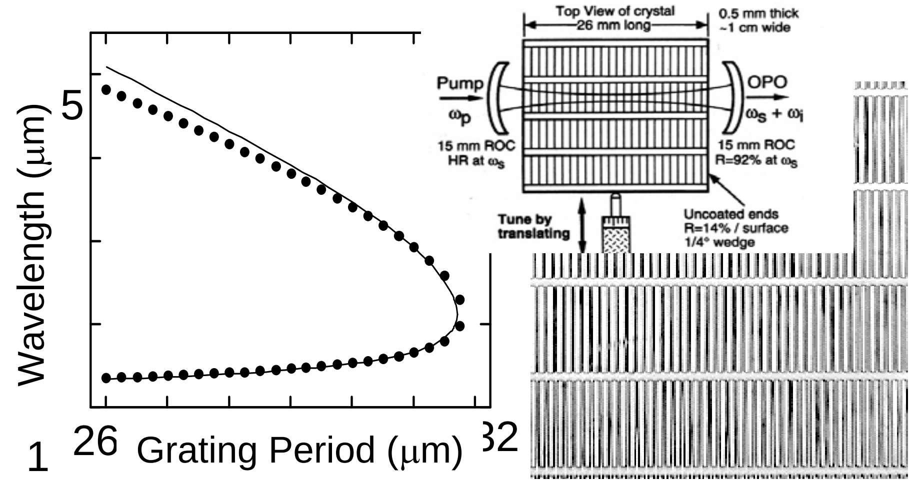
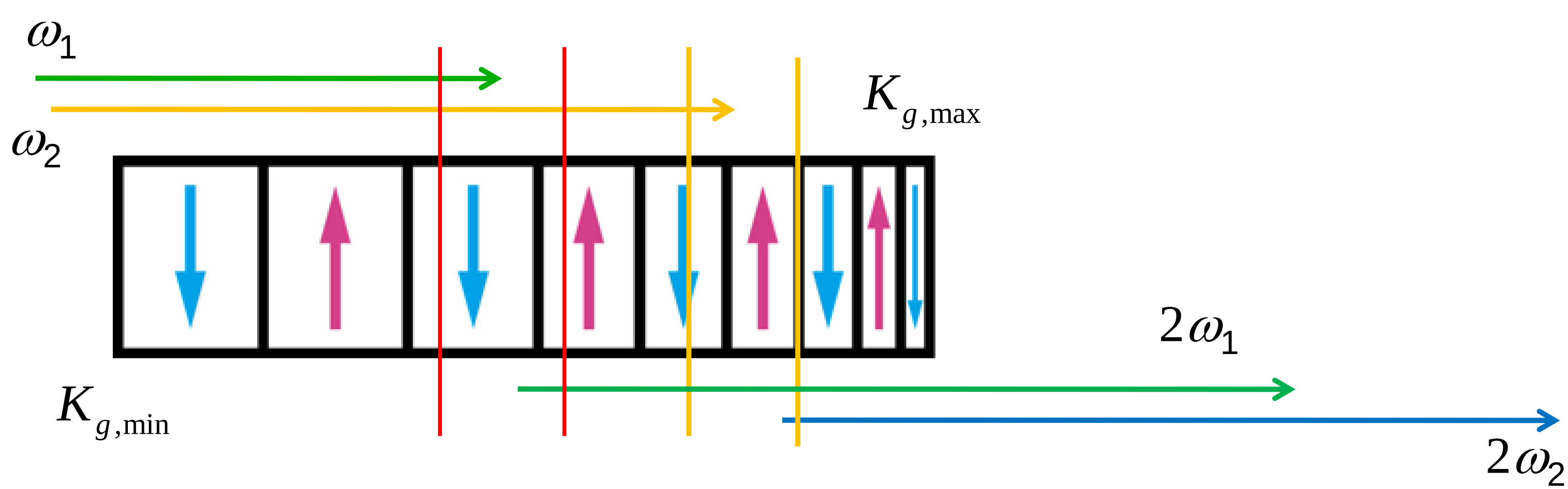


Aperiodic gratings can shape spectra

localized conversion of spectral slices



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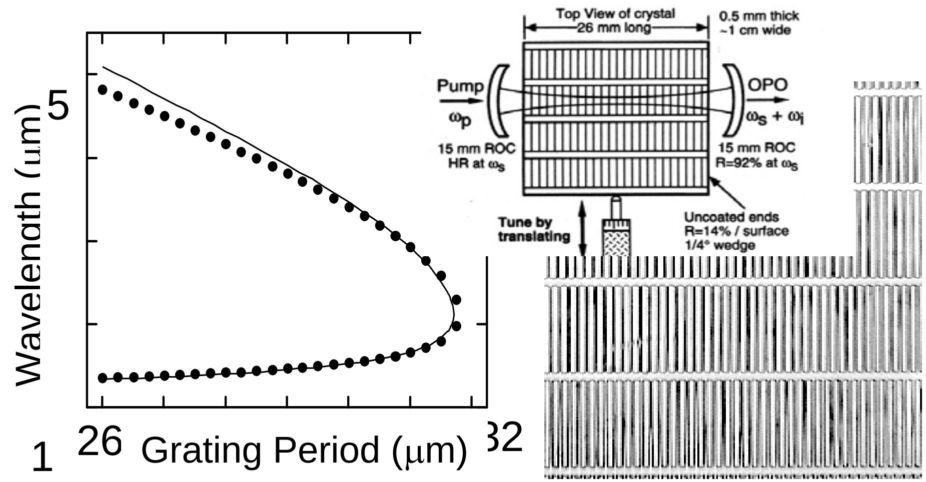
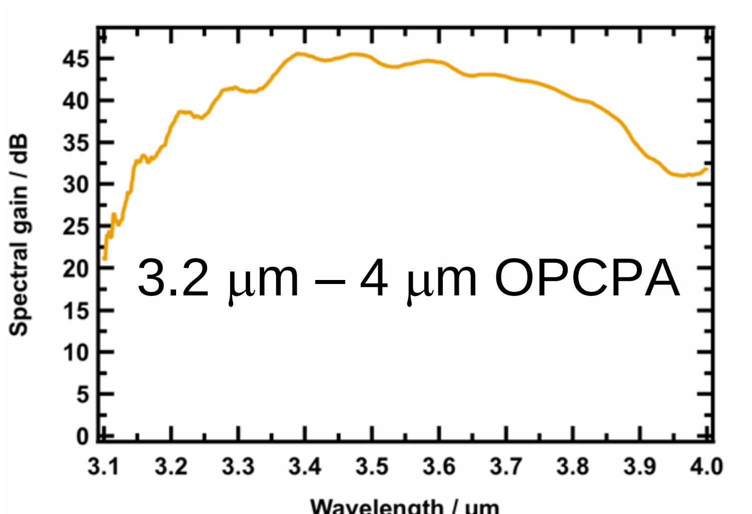


Aperiodic gratings can shape spectra

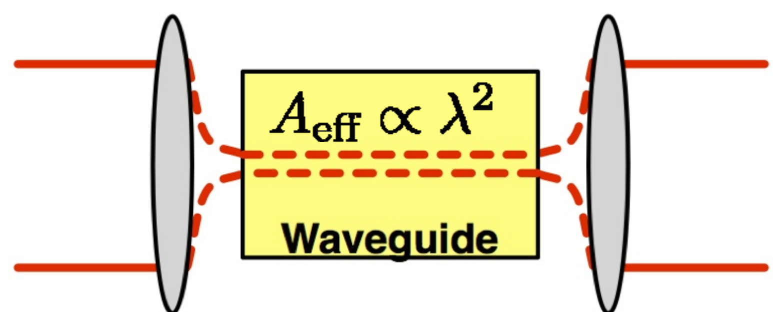
100 kHz OPCPA in chirped QPM



Waveguides:

tight confinement w/o diffraction

$\Rightarrow$ high efficiency at low power



$$\frac{P_{out}}{P_{in}} \propto \frac{P_{in}}{A_{eff}} L^2$$

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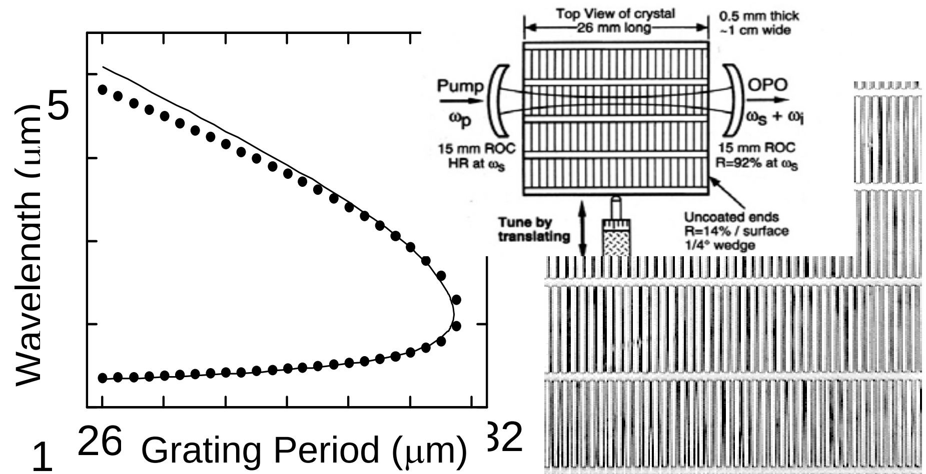
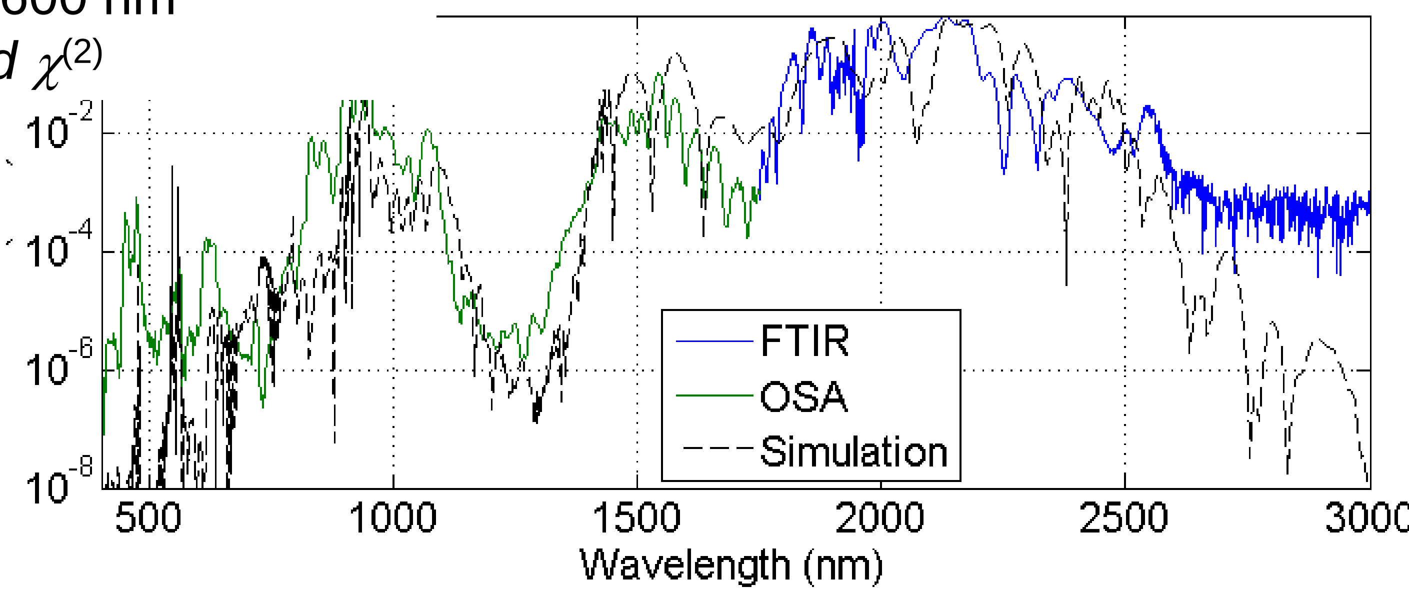


Aperiodic gratings can shape spectra

continuum 500 – 2600 nm

SPM via cascaded $\chi^{(2)}$

$$\chi_{eff}^{(3)}(z) \sim \frac{\chi^{(2)^2}}{\Delta k(z)}$$



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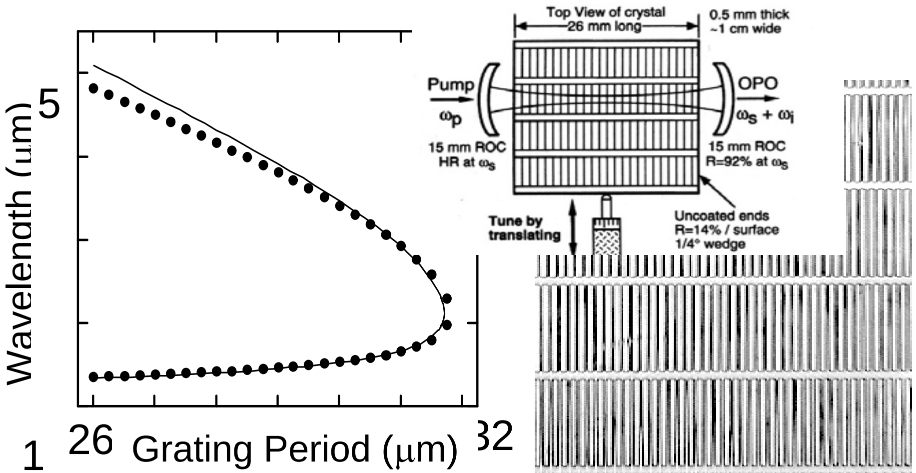

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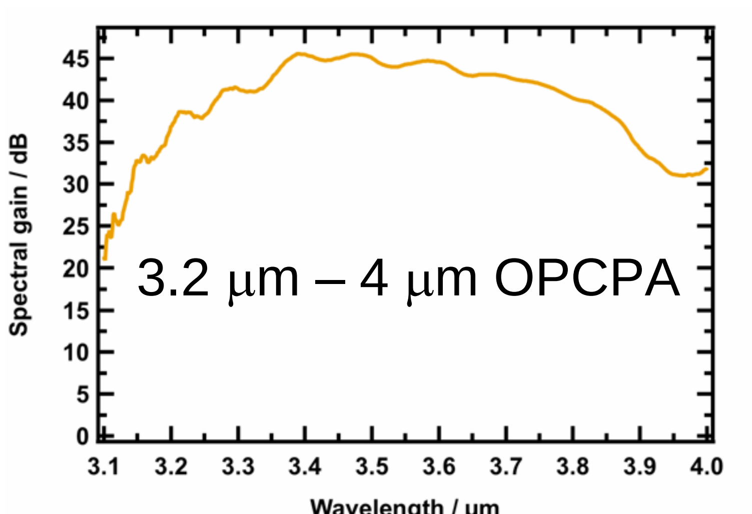
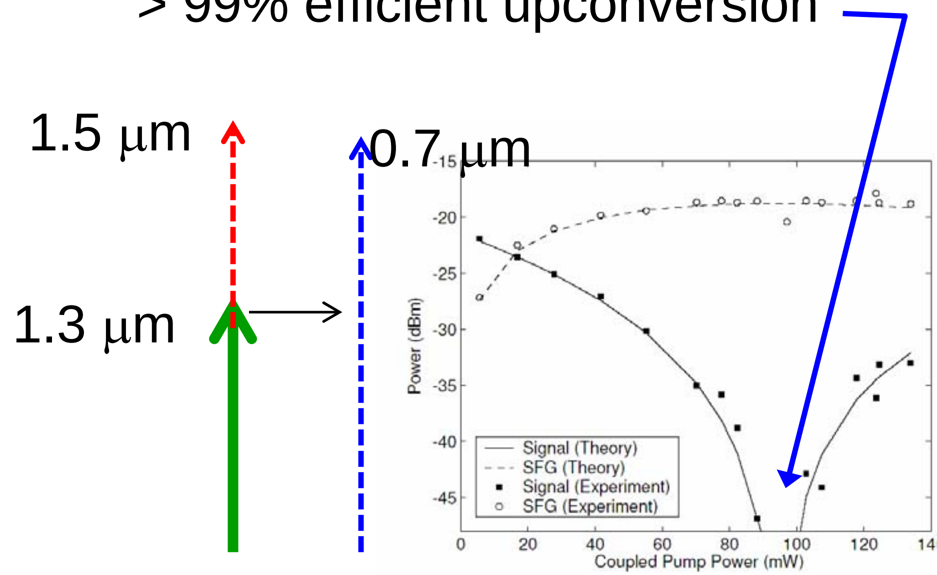


Manipulate single 1.5 µm photons

> 99% efficient upconversion



Outline: 35 Years of QPM

- Introduction

- History
  - ferroelectrics
  - semiconductors

- Current topics
  - microstructured materials
  - QPM devices

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First Laser in 1960

1960
Maiman &
ruby laser

1960	1970	1980	1990	2000	2010

Franken SHG, 1961: 50th Anniversary

1960
Maiman &
ruby laser

Volume 7, Number 4 PHYSICAL REVIEW LETTERS August 15, 1961

GENERATION OF OPTICAL HARMONICS*

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan
(Received July 21, 1961)

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SHG

Franken SHG, 1961: 50th Anniversary

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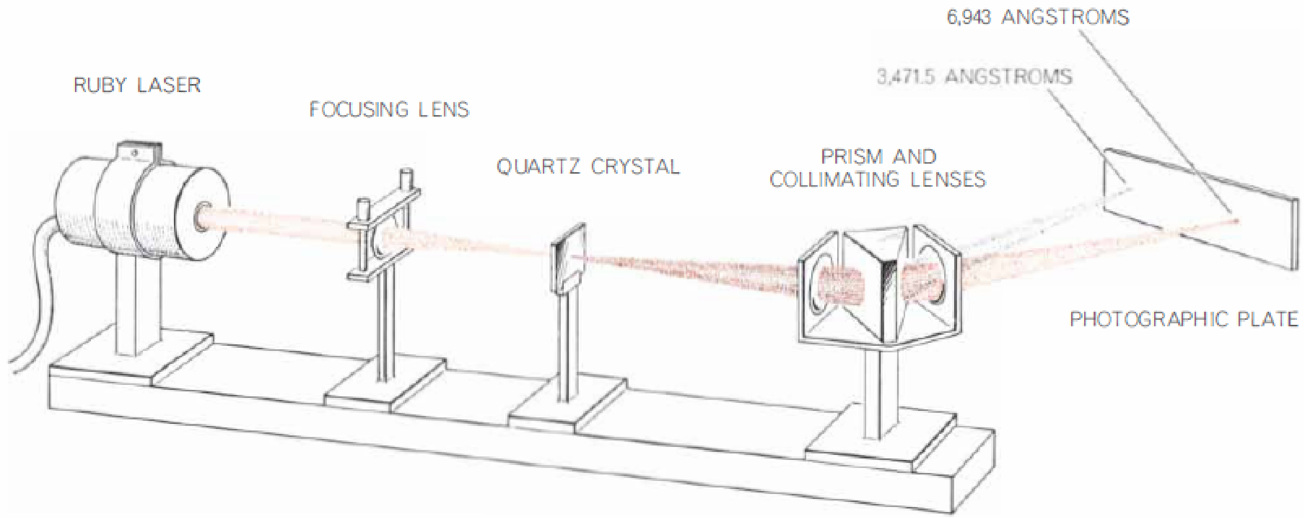

1960	1970	1980	1990	2000	2010

1961
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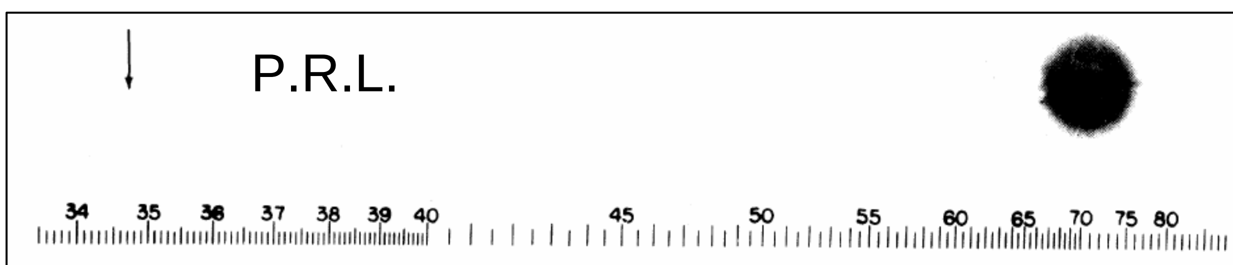

Bloembergen's Classic Theory Paper One Year Later

1960
Maiman & ruby laser

PHYSICAL REVIEW VOLUME 127, NUMBER 6 SEPTEMBER 15, 1962

Interactions between Light Waves in a Nonlinear Dielectric*

J. A. Armstrong, N. Bloembergen, J. Ducuing,† and P. S. Pershan
Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts
(Received April 16, 1962)

1962
Bloembergen:
Theory of NLO

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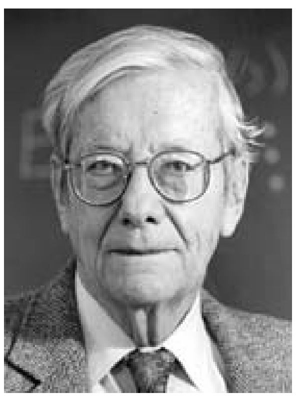

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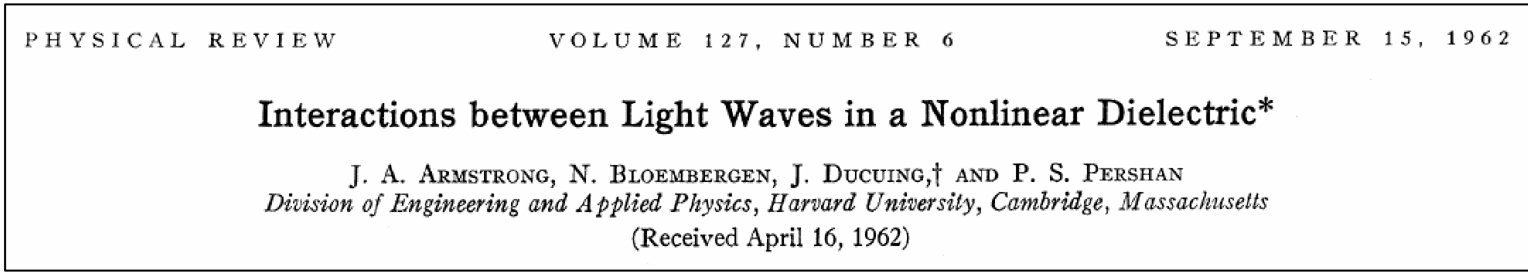

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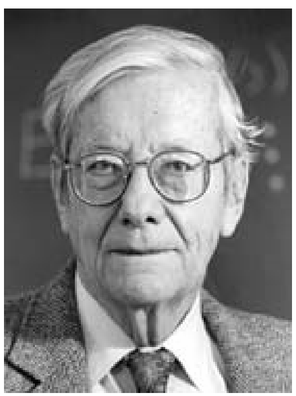

1961
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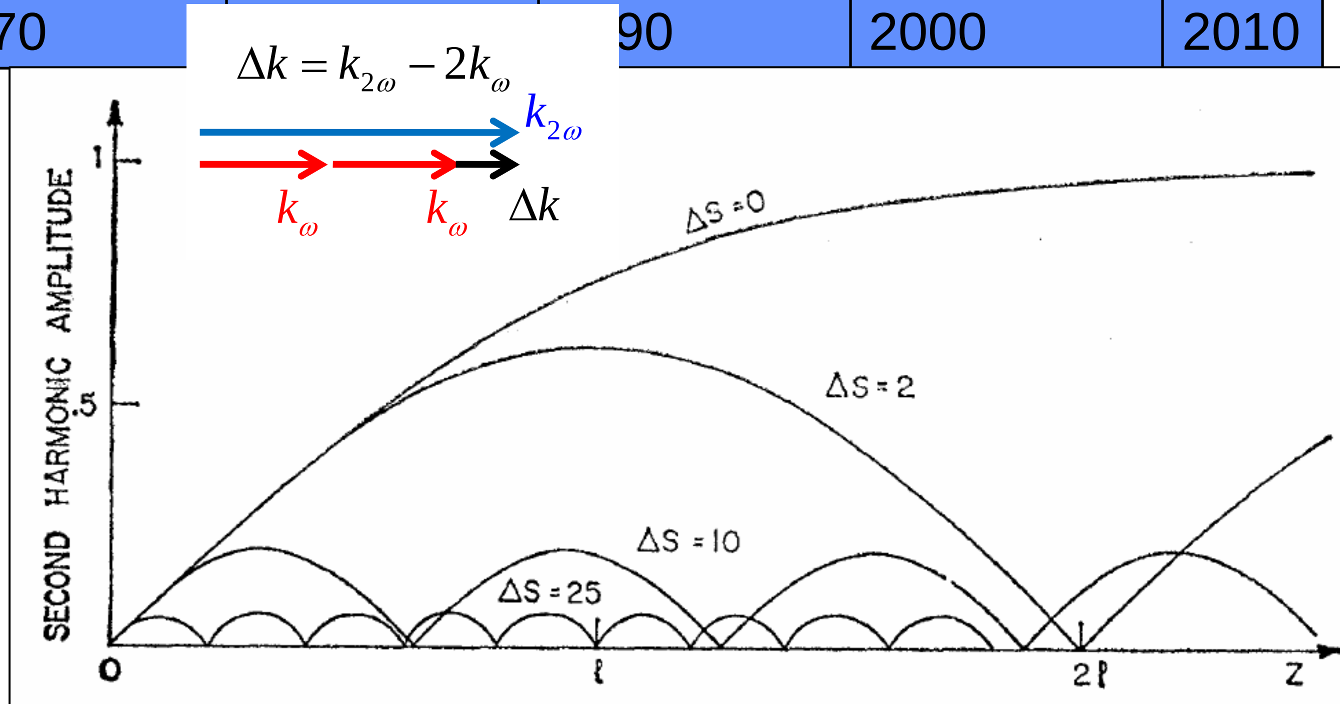


Birefringent Phasematching Same Year

1960
Maiman & ruby laser

1962
Bloembergen: Theory of NLO

VOLUME 8, NUMBER 1 PHYSICAL REVIEW LETTERS JANUARY 1, 1962

MIXING OF LIGHT BEAMS IN CRYSTALS

J. A. Giordmaine
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received November 29, 1961)

VOLUME 8, NUMBER 1 PHYSICAL REVIEW LETTERS JANUARY 1, 1962

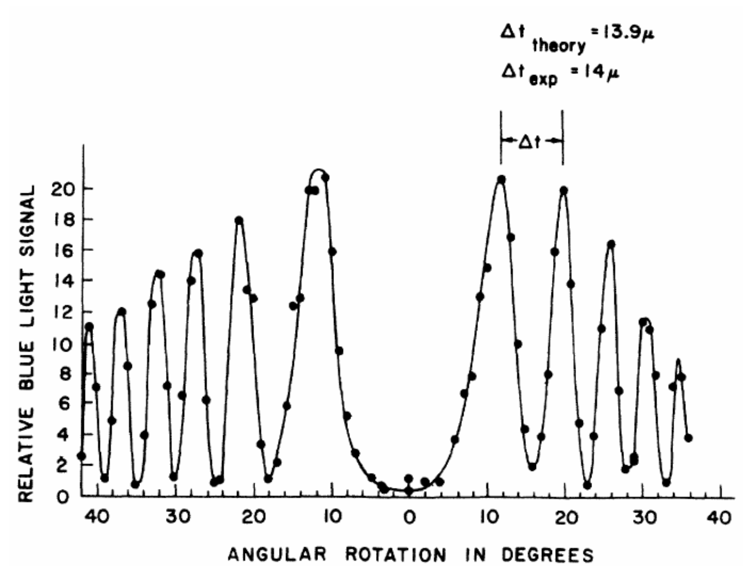
EFFECTS OF DISPERSION AND FOCUSING ON THE PRODUCTION OF OPTICAL HARMONICS

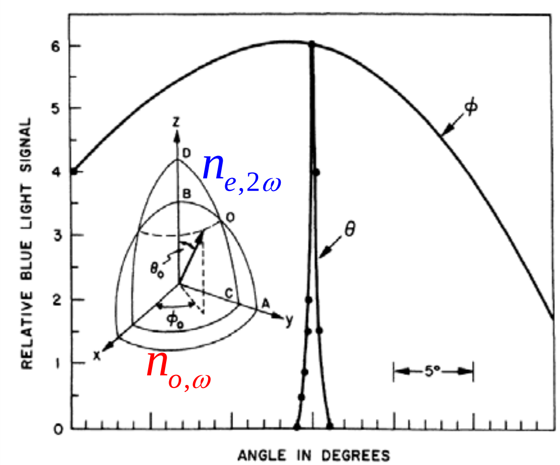
P. D. Maker, R. W. Terhune, M. Nisenoff, and C. M. Savage
Scientific Laboratory, Ford Motor Company, Dearborn, Michigan
(Received December 8, 1961)

1960	1970	1980	1990	2000	2010

1962
Giordmaine/Maker
Birefringent
Phasematching

1961
Franken & SHG





First OPO in 1965

1965
Giordmaine & Miller, First OPO

1960
Maiman & ruby laser

1962
Bloembergen: Theory of NLO

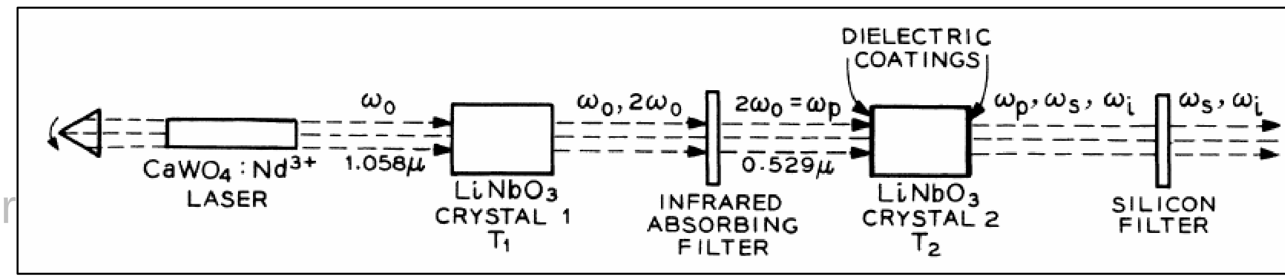
VOLUME 14 — 14 JUNE 1965 — NUMBER 24

TUNABLE COHERENT PARAMETRIC OSCILLATION IN $LiNbO_3$ AT OPTICAL FREQUENCIES

J. A. Giordmaine and Robert C. Miller

Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 11 May 1965)

1960	1970	1980	1990	2000	2010



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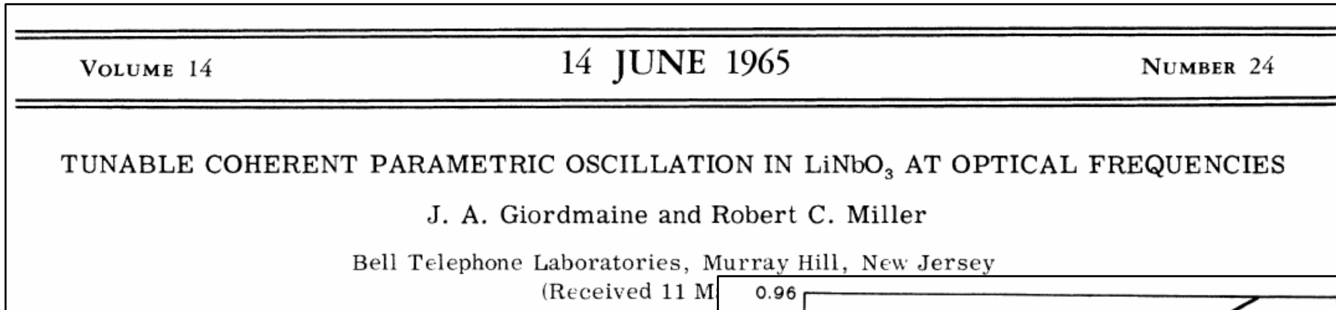
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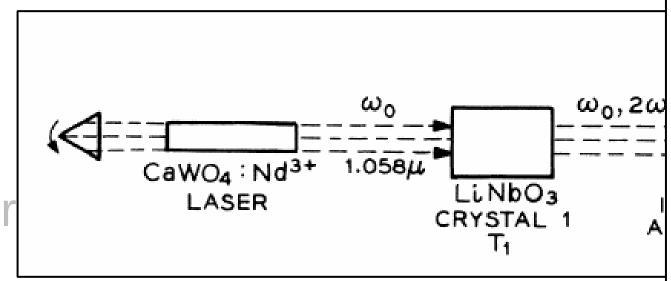

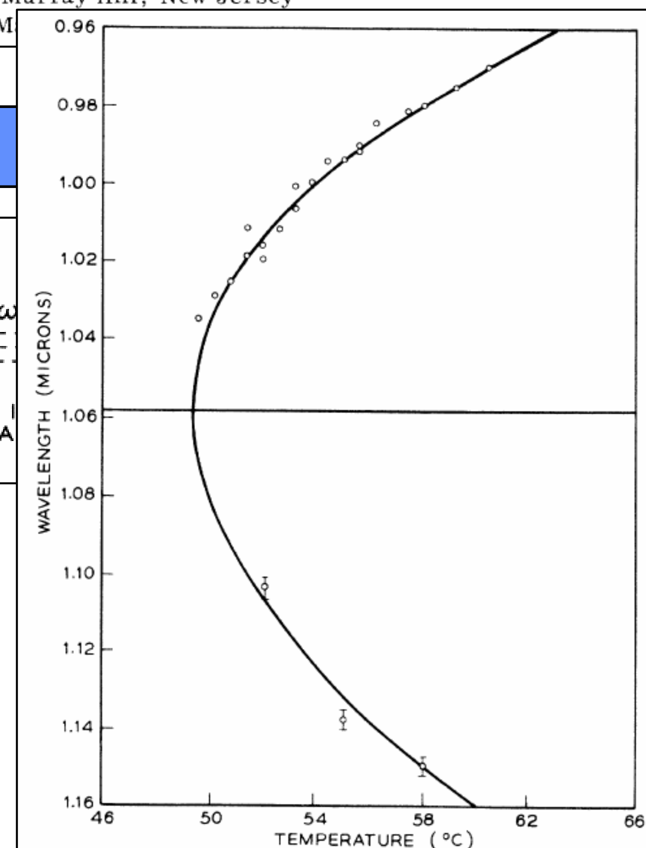

1962
Giordmaine/Maker
Birefringent
Phasematching

1961
Franken &
SHG

Bloembergen Also Proposed QPM in 1962

1960
Maiman &
ruby laser

1962
Bloembergen:
Theory of NLO

1960	1970

1961
Franken &
SHG

PHYSICAL REVIEW VOLUME 127, NUMBER 6 SEPTEMBER 15, 1962

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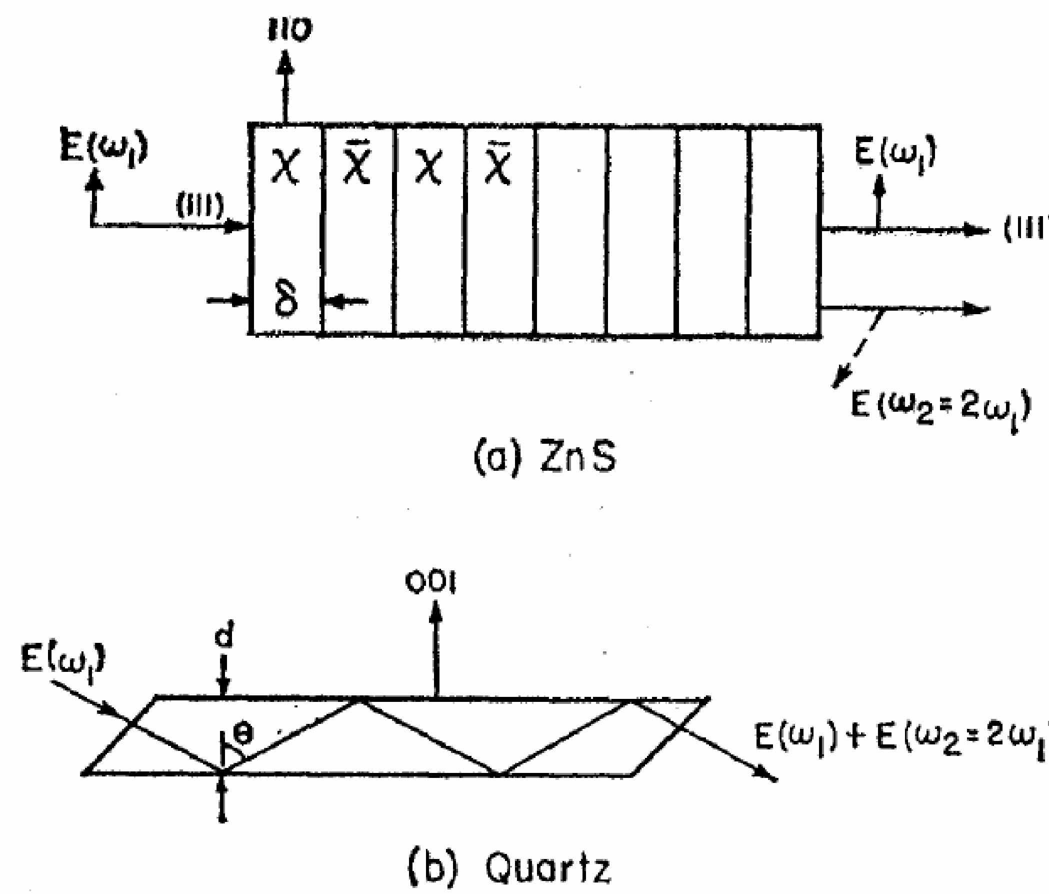


QPM Patent Issued 1968

1960
Maiman & ruby laser

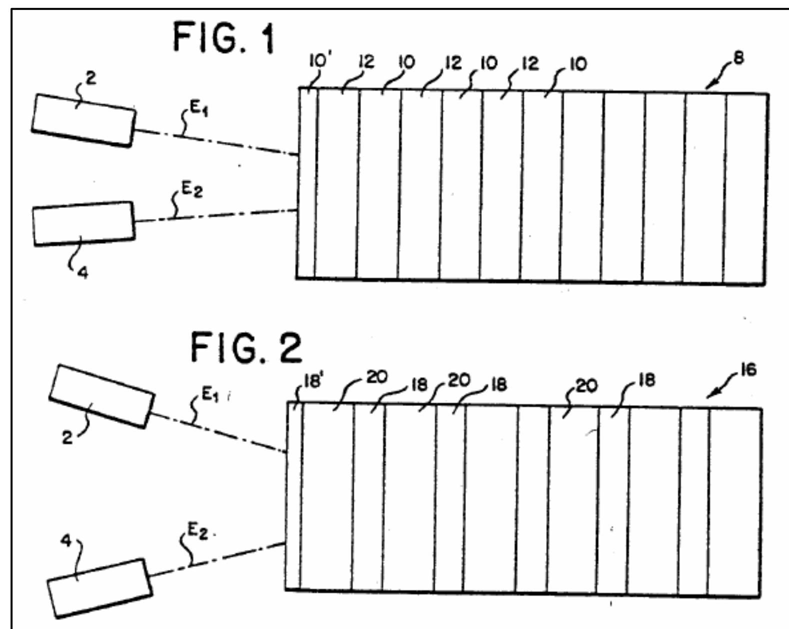
1962
Bloembergen: Theory of NLO

May 21, 1968 — N. BLOEMBERGEN — 3,384,433
APPARATUS FOR CONVERTING LIGHT ENERGY FROM ONE FREQUENCY TO ANOTHER
Filed July 9, 1962 — 2 Sheets-Sheet 1

1960	1970	1980	1990	2000	2010

1968
Bloembergen: QPM Patent

1961
Franken & SHG



Importance of Ferroelectric Domains Recognized: 1964

PHYSICAL REVIEW VOLUME 134, NUMBER 5A 1 JUNE 1964

Optical Harmonic Generation in Single Crystal $BaTiO_3$

ROBERT C. MILLER
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 21 January 1964)

1960
Maiman & ruby laser

1962
Bloembergen: Theory of NLO

1960 | 1970 | 1980

1968
Bloembergen: QPM Patent

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Miller: multi-domain ferroelectrics

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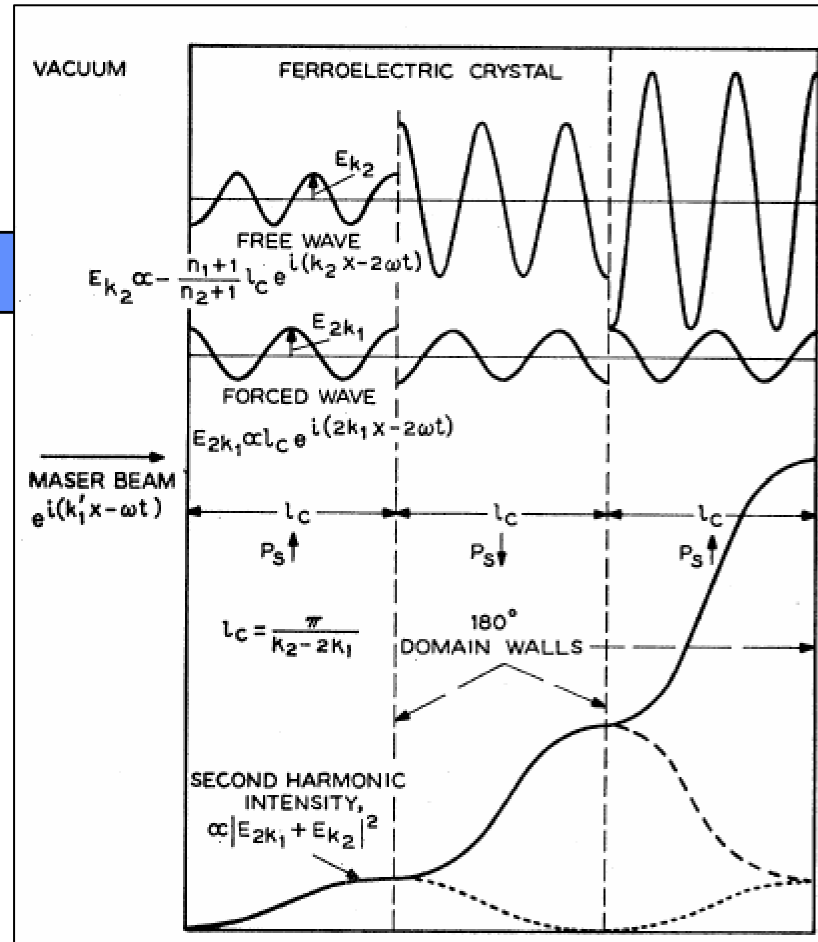

Twinned II-VI Semiconductors: 1972

1972
Twinned
semiconductors

1960
Maiman &
ruby laser

1962
Bloembergen:
Theory of NLO

GENERATION DE SECOND HARMONIQUE NON COLINEAIRE ET COLINEAIRE DANS ZnS. ACCORD DE PHASE ("PHASE MATCHING") PAR LA STRUCTURE LAMELLAIRE DU CRISTAL

J. MUZART, F. BELLON, C.A. ARGÜELLO et R.C.C. LEITE
Instituto de Física "Gleb Wataghin", Universidade Estaduel de Campinas, Campinas, S.P., Brasil

Reçu le 11 septembre 1972

1960	1970	1980	1990	2000	2010

1968
Bloe
QPM

Enhanced nonlinear optical effects in rotationally twinned crystals*

C. F. Dewey Jr.and L. O. Hocker
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 20 January 1975)

1964
Miller: mu
ferroelectrics

1961
Franken &
SHG

Stacks of II-VI and III-V Semiconductor Plates: 1976

1960 Maiman & ruby laser

1962 Bloembergen: Theory of NLO

1972 Twinned semiconductors

1976 Stack-of-plates (semiconductor)

Infrared second-harmonic generation in nonbirefringent cadmium telluride

M. S. Piltch, C. D. Cantrell, and R. C. Sze

University of California, Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos, New Mexico 87545

(Received 9 February 1976; in final form 10 May 1976)

A quasi-phase-matching technique for efficient optical mixing and frequency doubling

A. Szilagyi, A. Hordvik, and H. Schlossberg

Air Force Cambridge Research Laboratories, Hanscom Air Force Base, Massachusetts 01731

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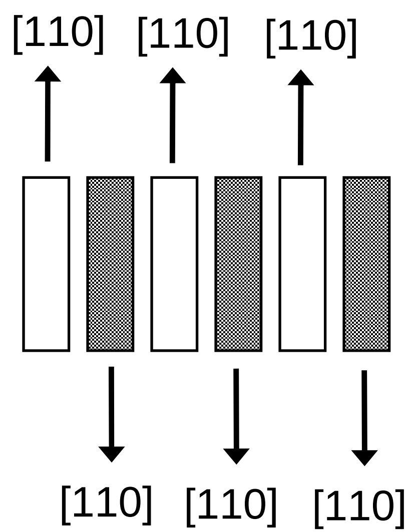

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Maiman &
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Theory of NL

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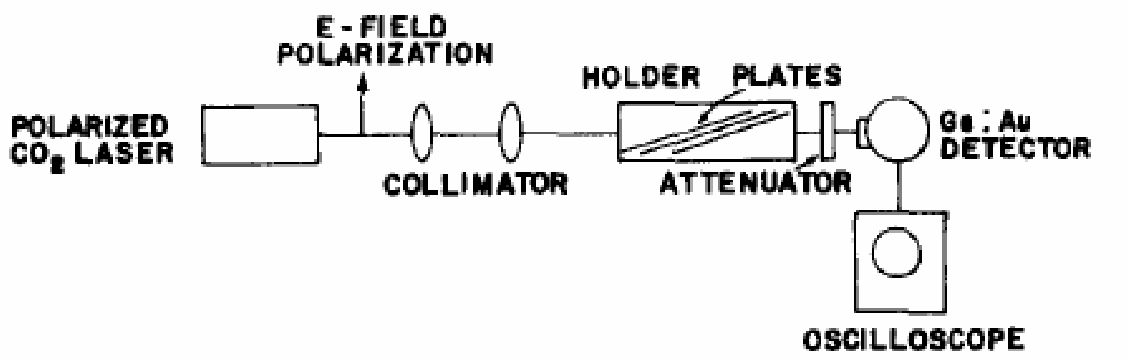

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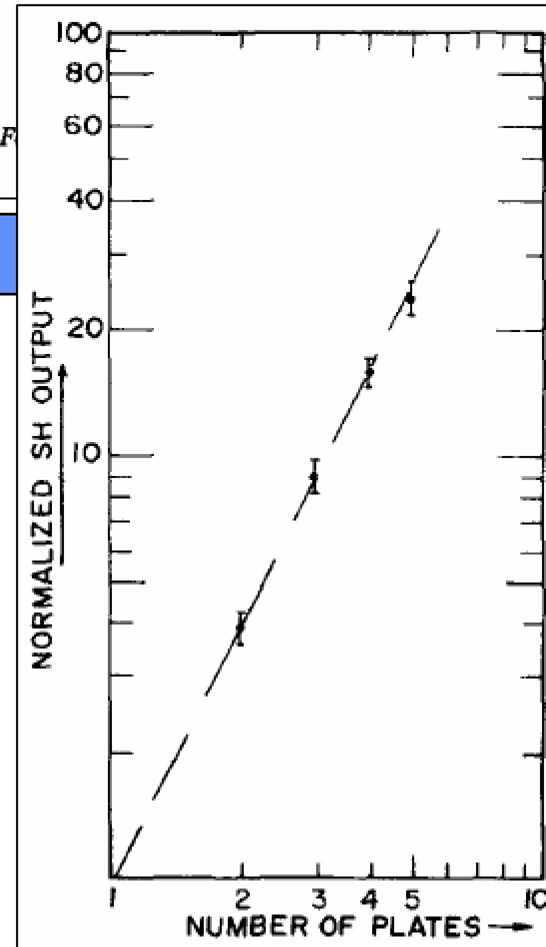

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Bloembergen:
QPM Patent

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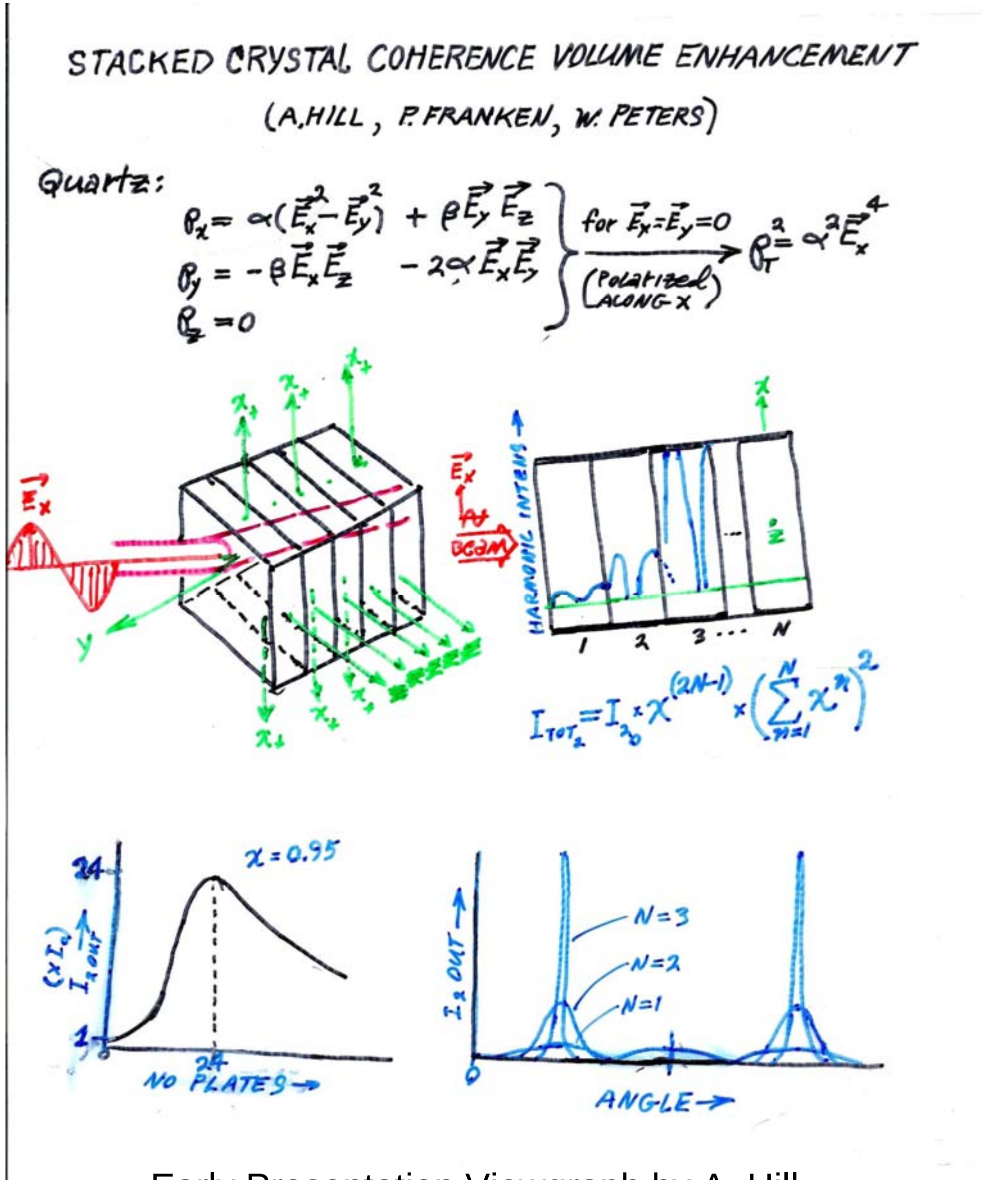
Franken &
SHG

Franken and Hill: Stacks of Quartz Plates: 1961(!)



Early Presentation Viewgraph by A. Hill

*Note: The only publication of this work was a reference in J. A. Giordmaine's 1964 *Scientific American* article

~~35~~ Years of Quasi-Phasematched Nonlinear Optics

50

M. M. Fejer
E. L. Ginzton Laboratory
Stanford University

fejer@stanford.edu

Periodically Perturbed Growth of $LiNbO_3$: 1980

1972
Twinned

1960
Maim
ruby l

19
Blo
Th

Enhancement of second-harmonic generation in $LiNbO_3$ crystals with periodic laminar ferroelectric domains

Duan Feng, Nai-Ben Ming, Jing-Fen Hong, Yong-Shun Yang, Jin-Song Zhu, Zhen Yang, and Ye-Ning Wang
Institute of Solid State Physics, Nanking University, Nanking, China

(Received 23 June 1980; accepted for publication 16 July 1980)

1960	1970	1980	1990	2000	2010

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Bloembergen:
QPM Patent

1964
Miller: multi-domain
ferroelectrics

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Franken &
SHG

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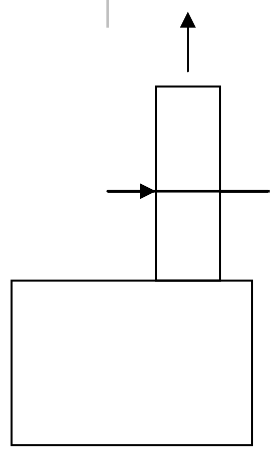
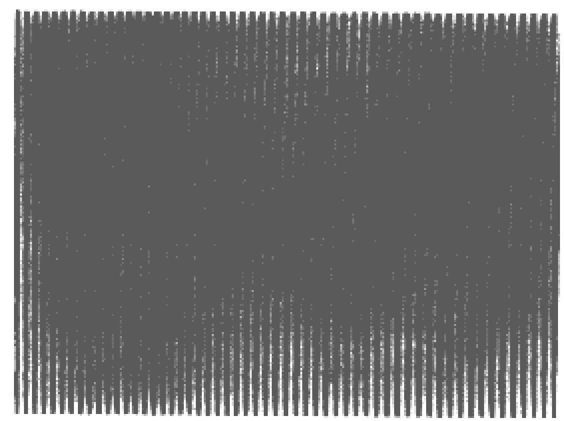
QPM by crystal
growth





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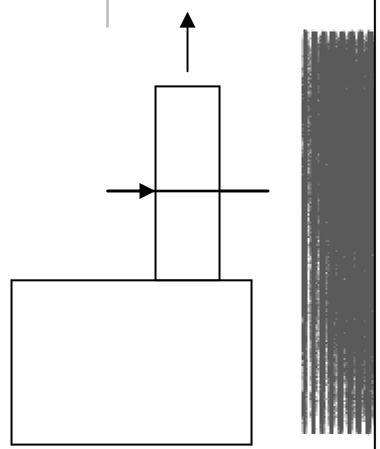

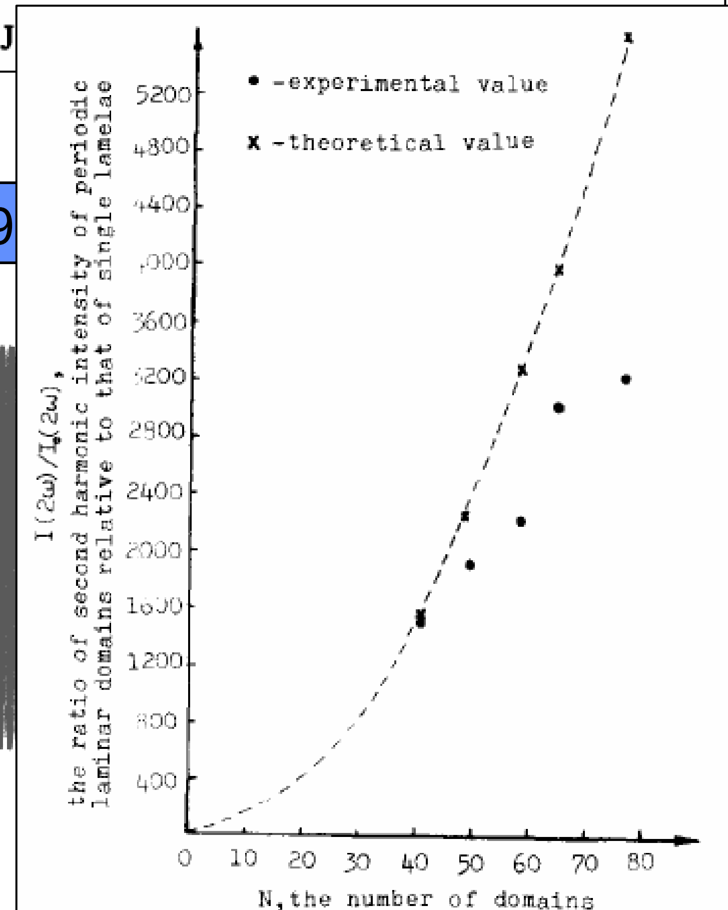

Single Crystal Fibers Enable Better Control: 1989

1960
Maiman & ru

1972
Twinned semiconductors

1989
Single-crystal fibers

Quasi-phase-matched second-harmonic generation of blue light in periodically poled $LiNbO_3$

G. A. Magel, M. M. Fejer, and R. L. Byer
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

(Received 24 August 1989; accepted for publication 31 October 1989)

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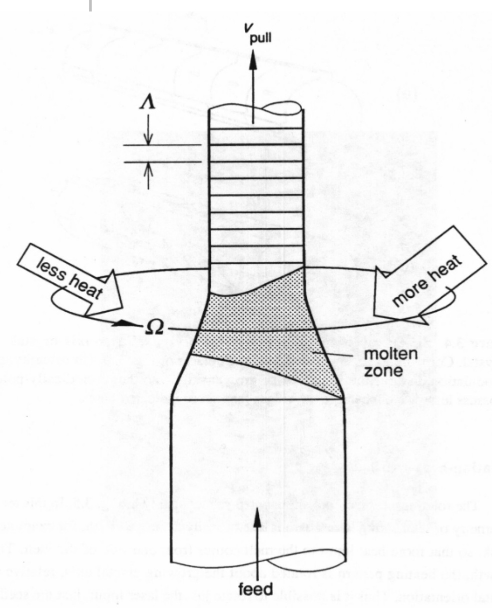

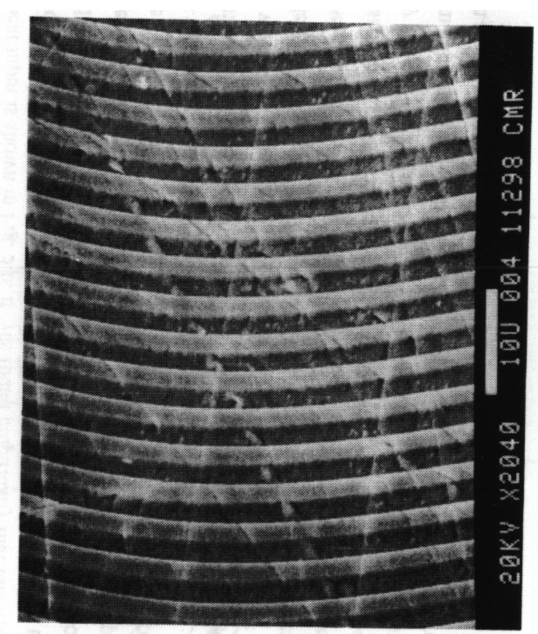

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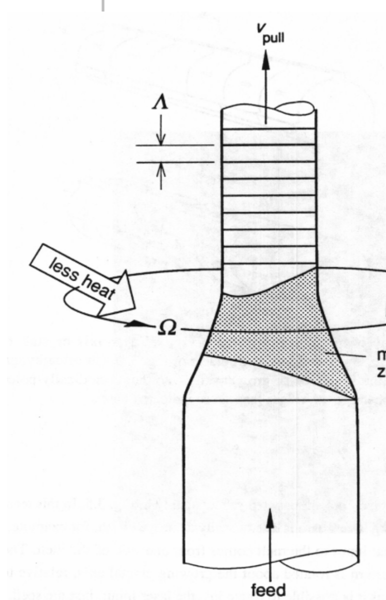

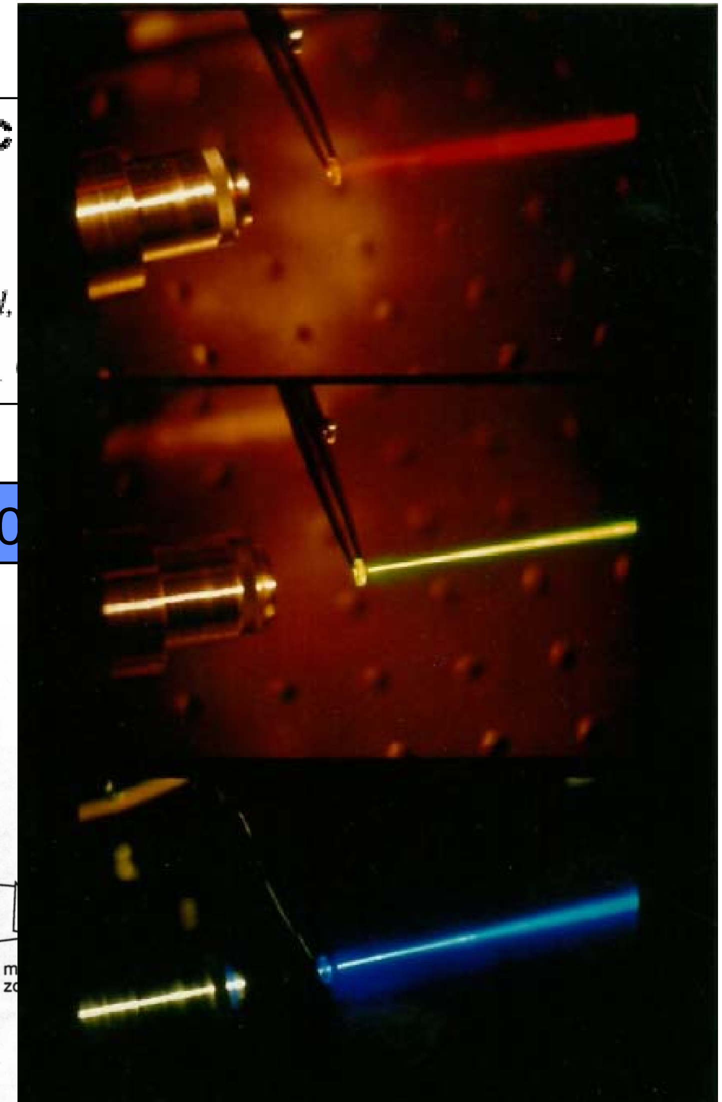

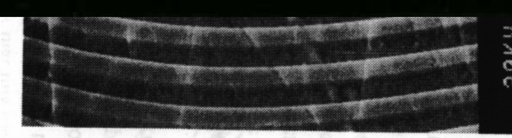

Multiwatt QPM Intracavity SHG in PPLN Fibers

1972
Twinned
semiconductors

1989
Single-crystal
fibers

1960
Maiman &
ru

Quasi-phase-matched second-harmonic generation of blue light in periodically poled $LiNbO_3$

Periodically poled $LiNbO_3$ for high-efficiency second-harmonic generation

D. H. Jundt, G. A. Magel,[a] M. M. Fejer, and R. L. Byer
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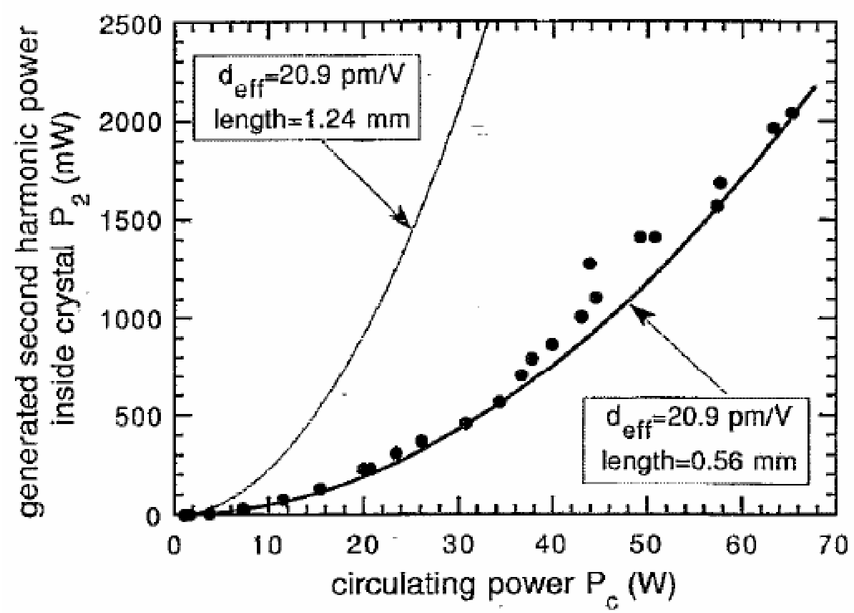

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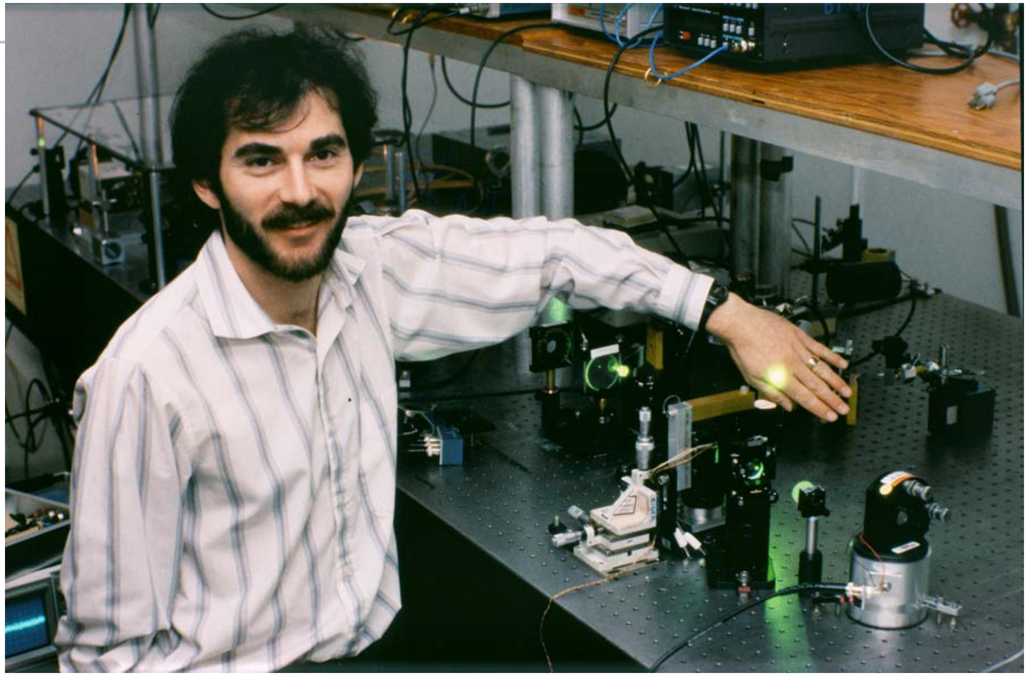

Lithographic Control: Ti-Indiffused $LiNbO_3$: 1989

1960
Maiman & ruby laser

1962
Bloembergen: Theory of NLO

1972
Twinned semiconductors

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Stack-of-plates (semiconductor)

1989
Single-crystal fibers

1989
Diffusion poling

SECOND-HARMONIC GENERATION OF GREEN LIGHT IN PERIODICALLY POLED PLANAR LITHIUM NIOBATE WAVEGUIDE

E.J. LIM, M.M. FEJER, R.L.BYER

Indexing terms: Optics, Optical waveguides, Integrated optics, Nonlinear optics

A periodically poled, planar waveguide in lithium niobate was used to generate 532 nm radiation at room temperature by continuous-wave frequency-doubling with a conversion efficiency of 5% per W cm^2. Quasi-phase-matching allowed generation of the second harmonic using the d_{33} nonlinear coefficient.

ELECTRONICS LETTERS 2nd February 1989 Vol. 25 No. 3

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Miller: multi-domain ferroelectrics

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Franken & SHG

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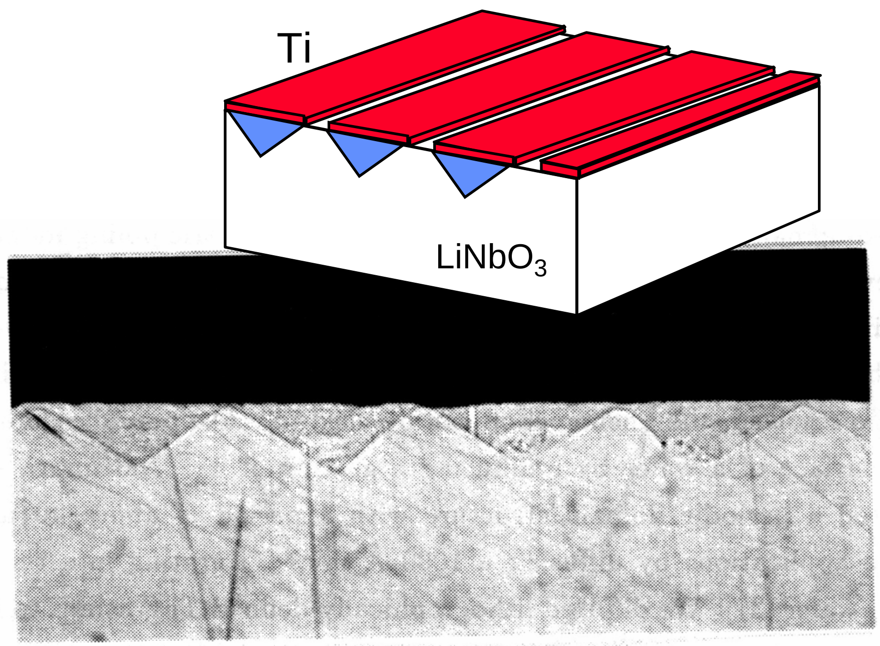

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ELECTRONICS LETTERS 2nd February 1989 Vol. 25 No. 3

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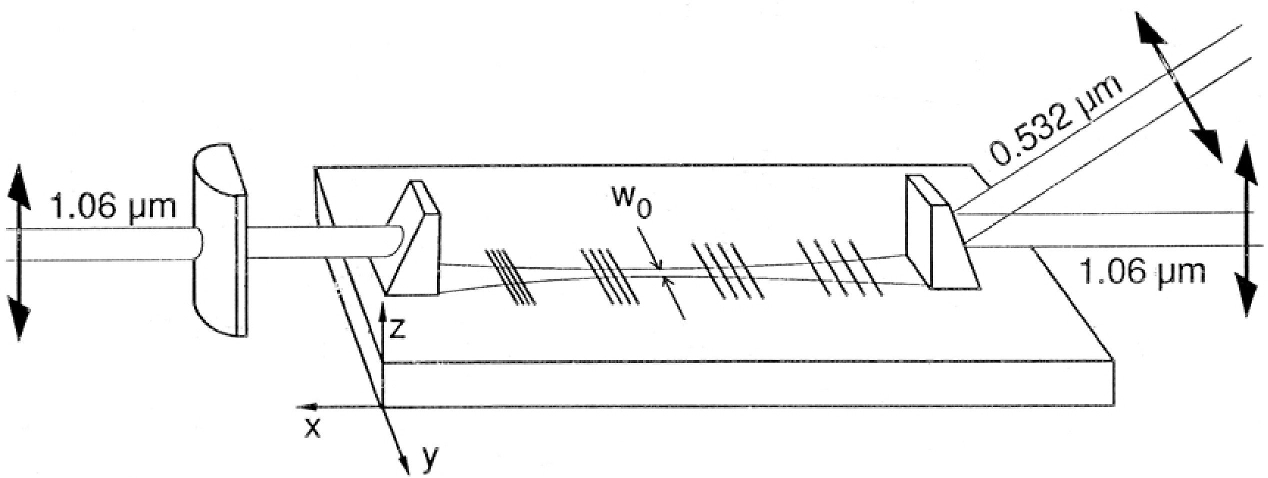

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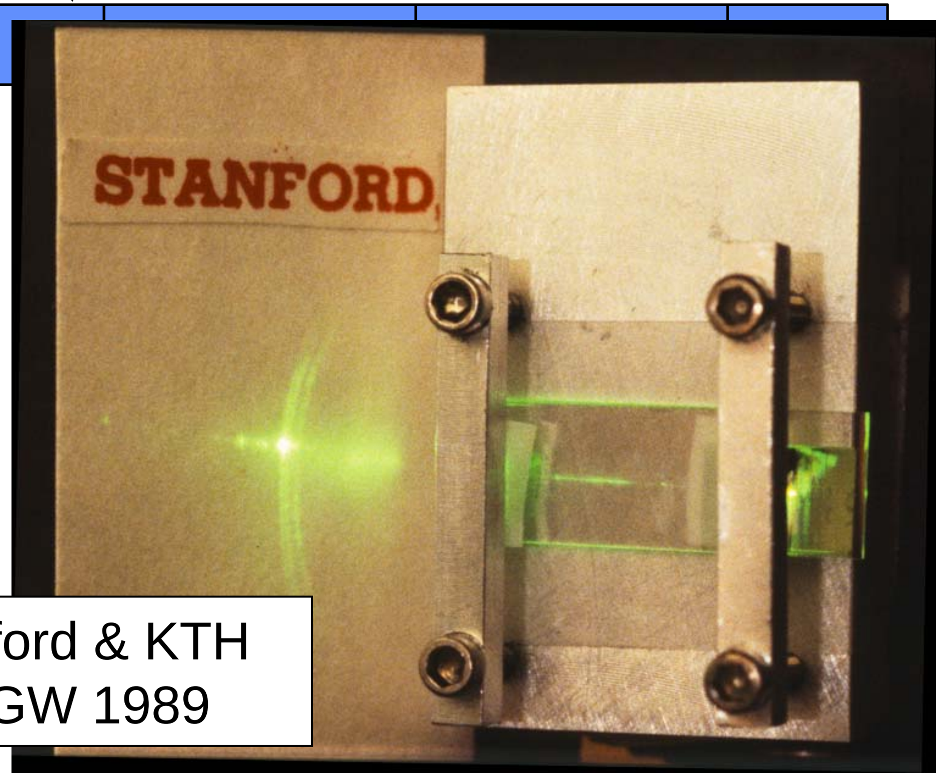

Stanford & KTH
NLGW 1989

Channel Waveguides in $LiNbO_3$ and KTP: 1989

1960
Maiman & ruby laser

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Bloembergen: Theory of NLO

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Twinned semiconductors

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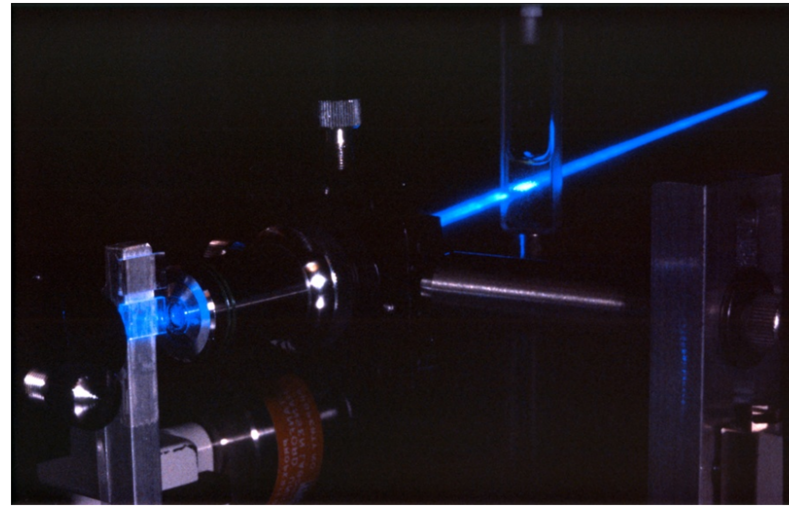
Stack-of-plates (semiconductor)

1989
Single-crystal fibers

1989
Diffusion poling



1960	1970	1980	1990	2000	2010

1961
Franken & SHG

1964
Miller: multi-domain ferroelectrics

1968
Bloembergen: QPM Patent

1980
QPM by crystal growth

BLUE LIGHT GENERATION BY FREQUENCY DOUBLING IN PERIODICALLY POLED LITHIUM NIOBATE CHANNEL WAVEGUIDE

Indexing terms: Optics, Integrated optics, Optical waveguides, Nonlinear optics

Blue light at 410 nm was generated by continuous-wave frequency-doubling in a periodically poled lithium niobate channel waveguide at room temperature. Quasi-phasematching allowed generation of the blue light using the d_{33} nonlinear coefficient.

ELECTRONICS LETTERS 25th May 1989

Channel Waveguides in $LiNbO_3$ and KTP: 1989

316 IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 1, NO. 10, OCTOBER 1989

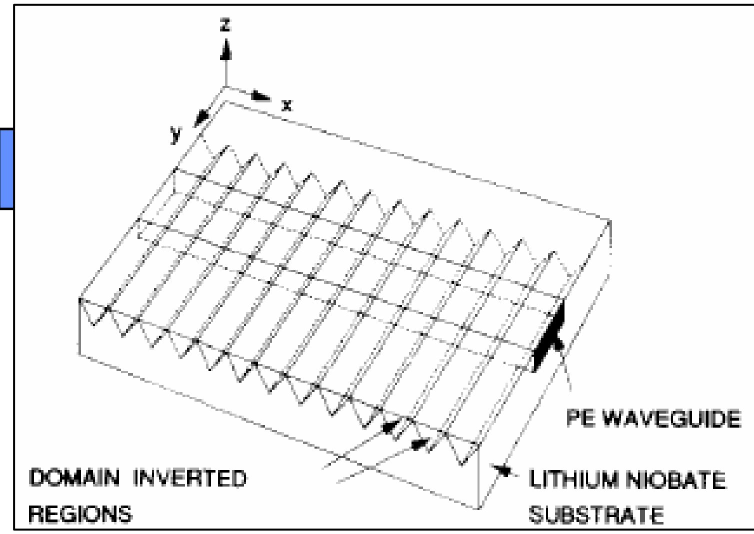
Blue Light Generated by Frequency Doubling of Laser Diode Light in a Lithium Niobate Channel Waveguide

JONAS WEBJÖRN, FREDRIK LAURELL, AND GUNNAR ARVIDSSON

Theory of NLO

Diffusion poling

1960 | 1970 | 1980



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Bloembergen: QPM Patent

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Franken & SHG

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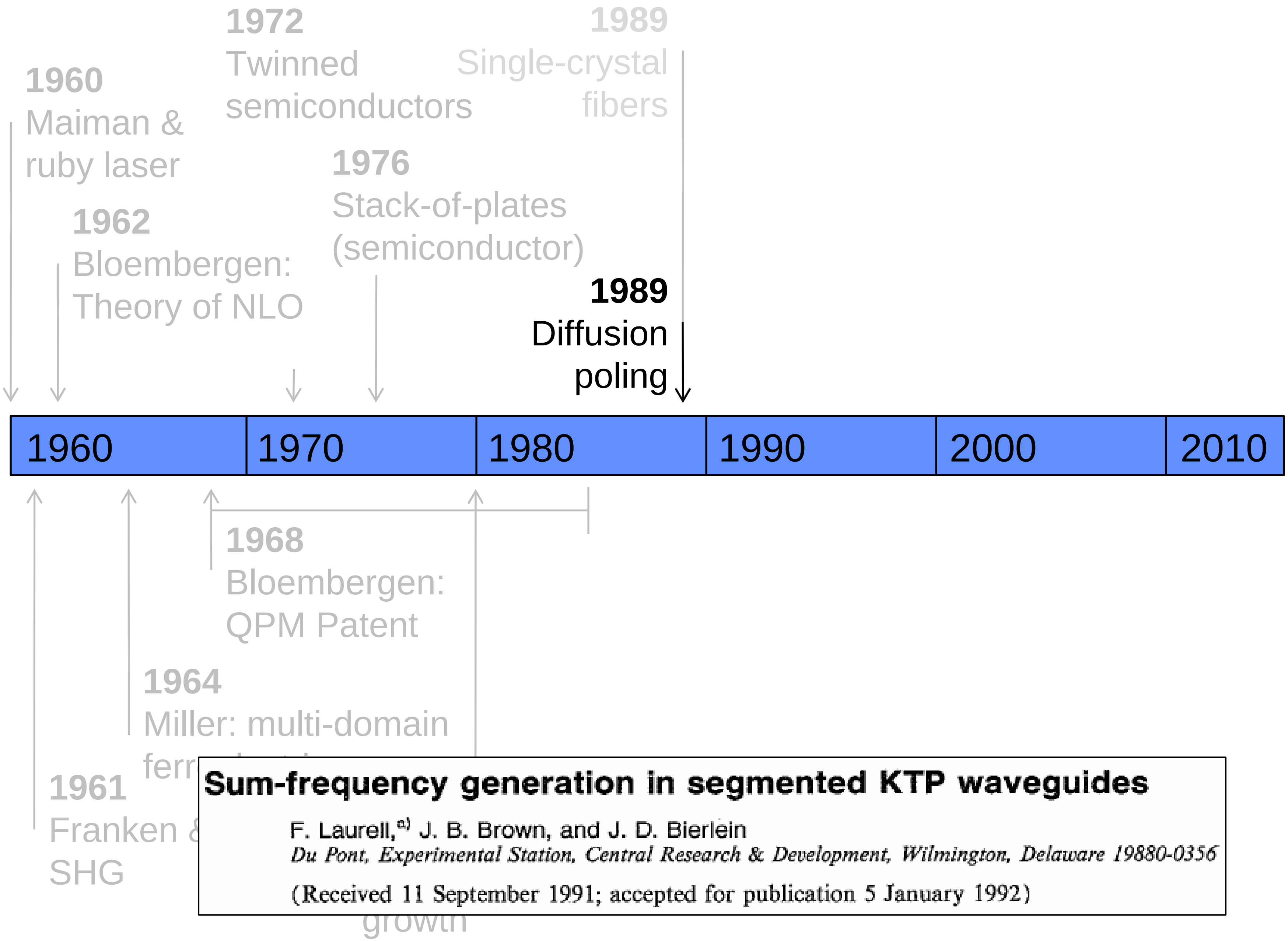
QPM by crystal growth

Channel Waveguides in $LiNbO_3$ and KTP: 1989



Sum-frequency generation in segmented KTP waveguides

F. Laurell,[a] J. B. Brown, and J. D. Bierlein
Du Pont, Experimental Station, Central Research & Development, Wilmington, Delaware 19880-0356

(Received 11 September 1991; accepted for publication 5 January 1992)

Volume Poling with Electric Fields: 1992

1972
Twinned

1989
Single-crystal

1960
Ma
rub

First-order quasi-phase matched $LiNbO_3$ waveguide periodically poled by applying an external field for efficient blue second-harmonic generation

M. Yamada, N. Nada, M. Saitoh, and K. Watanabe
Applied Magnetic Research Department, Corporate Research Laboratories, Sony Corporation, Kita-Shinagawa 6-7-35, Shinagawa-ku, Tokyo, 141, Japan

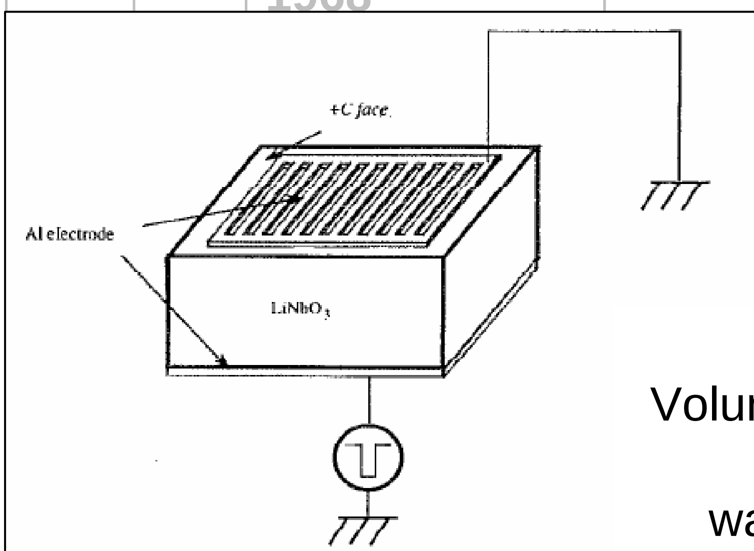
(Received 28 July 1992; accepted for publication 21 November 1992)

Theory of NLO

Diffusion
poling

1960	1970	1980	1990	2000	2010

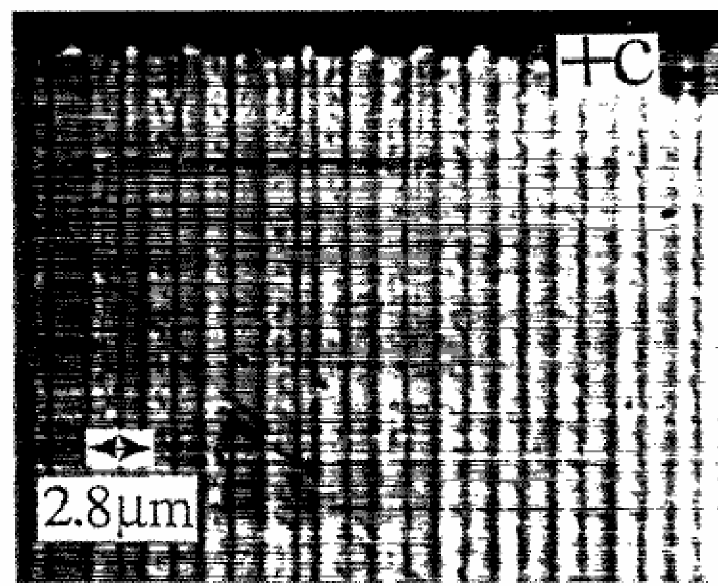
1968



1991
ctric field
poling

E-beam
poling

1992
Volume E-field
poling for
waveguides



Bulk Interactions in E-Field Poled $LiNbO_3$ and KTP: 1994

1960
Maiman & ruby laser

1962
Bloembergen: Theory of NLO

1972
Twinned semiconductors

1976
S
(s

1989
Single-crystal fibers

poling

1994
Bulk QPM: Electrically poled $LiNbO_3$

252 IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 6, NO. 2, FEBRUARY 1994

Second Harmonic Generation in Field Poled, Quasi-Phase-Matched, Bulk $LiNbO_3$

W. K. Burns, *Senior Member, IEEE*, W. McElhanon and L. Goldberg

1960	1970	1980	1990	2000	2010

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Bloembergen: QPM Patent

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Miller: multi-domain ferroelectrics

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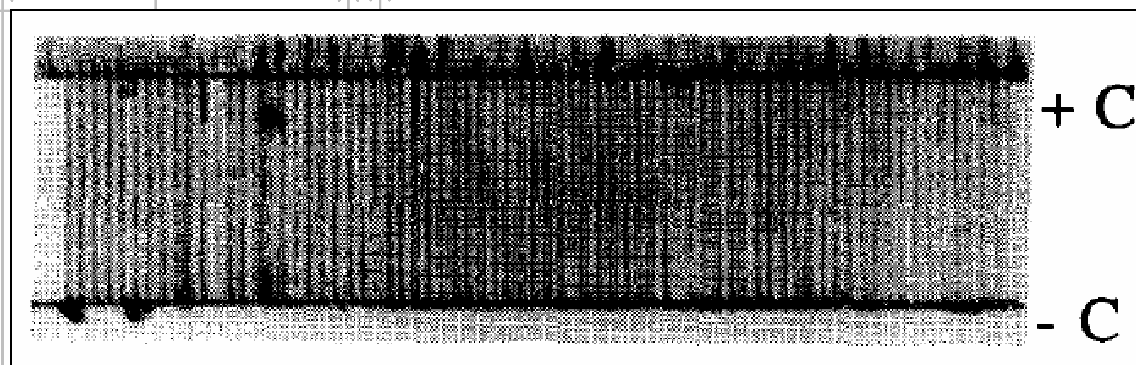

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Volume E-field poling for waveguides

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Twinned semiconductors

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Stack-of-plates (semiconductor)

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Single-crystal fibers

1989
Diffusion poling

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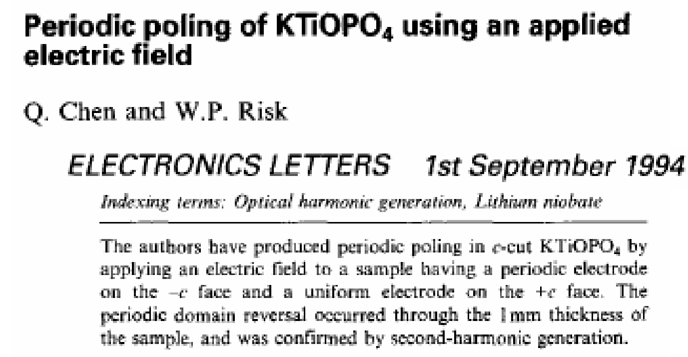
Bulk QPM: Electrically poled KTP



Periodic poling of $KTiOPO_4$ using an applied electric field

Q. Chen and W.P. Risk

ELECTRONICS LETTERS 1st September 1994

Indexing terms: Optical harmonic generation, Lithium niobate

The authors have produced periodic poling in c-cut $KTiOPO_4$ by applying an electric field to a sample having a periodic electrode on the −c face and a uniform electrode on the +c face. The periodic domain reversal occurred through the 1 mm thickness of the sample, and was confirmed by second-harmonic generation.

1960	1970	1980	1990	2000	2010

1961
Franken & SHG

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Miller: multi-domain ferroelectrics

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Bloembergen: QPM Patent

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QPM by crystal growth

1991
Electric field poling

E-beam poling

1992
Volume E-field poling for waveguides

First QPM OPOs: Bulk and Waveguide: 1995

1960
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Twinned
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Stack
(sem

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poling

1994

1995
QPM OPO:
bulk and WG

52 OPTICS LETTERS / Vol. 20, No. 1 / January 1, 1995

Quasi-phase-matched 1.064-μm-pumped optical parametric oscillator in bulk periodically poled $LiNbO_3$

L. E. Myers, G. D. Miller, R. C. Eckardt, M. M. Fejer, and R. L. Byer
E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305

W. R. Bosenberg
Lightwave Electronics Corporation, Mountain View, California 94043

1960	1970	1980	1990	2000	2010

1961
Franken &
SHG

1964
Miller: mu
ferroelec

196
Blo
QPI

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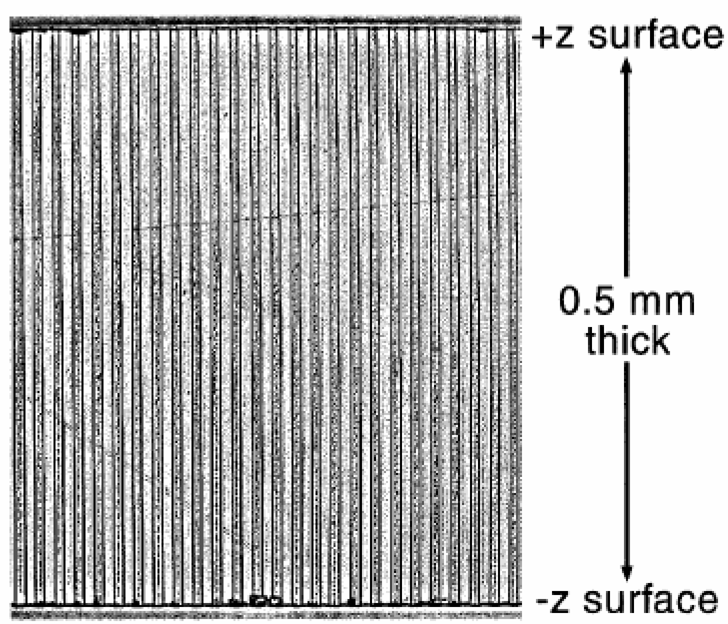

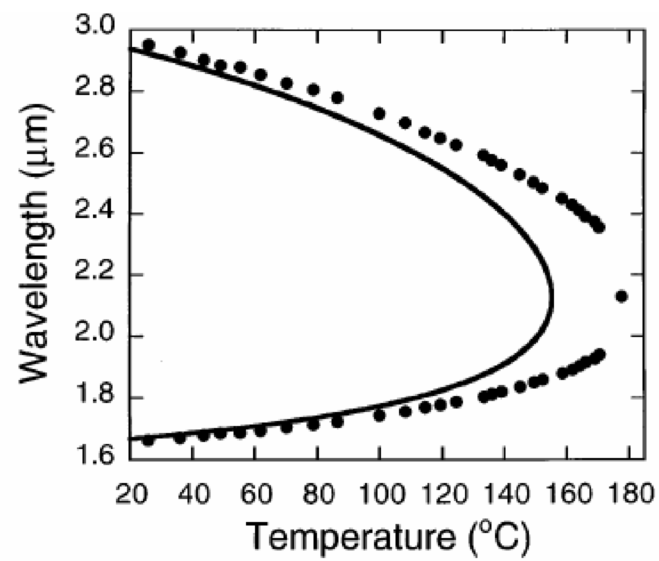

First QPM OPOs: Bulk and Waveguide: 1995

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Maiman & ruby laser

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Bloembergen Theory of NL

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Single-crystal fibers

1994
Bulk QPM: Electrically poling

1995
QPM OPO: bulk and WG

January 1, 1995 / Vol. 20, No. 1 / OPTICS LETTERS 49

Quasi-phase-matched optical parametric amplification and oscillation in periodically poled $LiNbO_3$ waveguides

M. L. Bortz, M. A. Arbore, and M. M. Fejer

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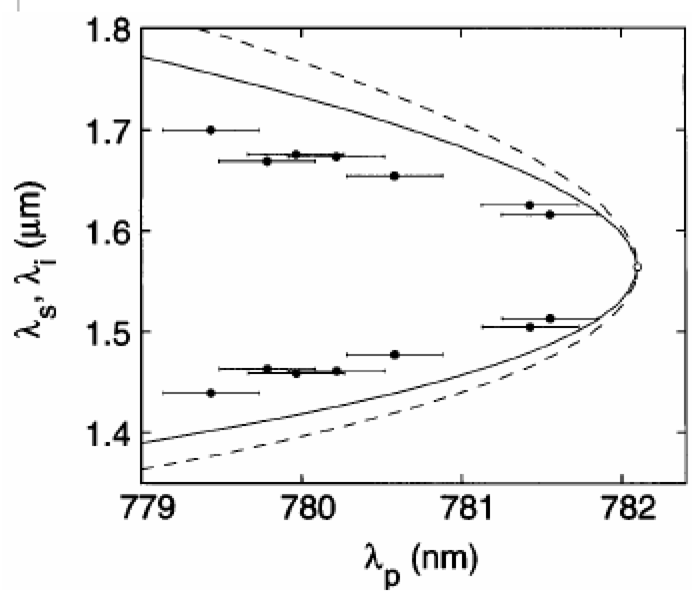
Volume E-field poling for waveguides



Extension to Visible SHG: 1997

1834 OPTICS LETTERS / Vol. 22, No. 24 / December 15, 1997

42%-efficient single-pass cw second-harmonic generation in periodically poled lithium niobate

G. D. Miller, R. G. Batchko, W. M. Tulloch, D. R. Weise, M. M. Fejer, and R. L. Byer

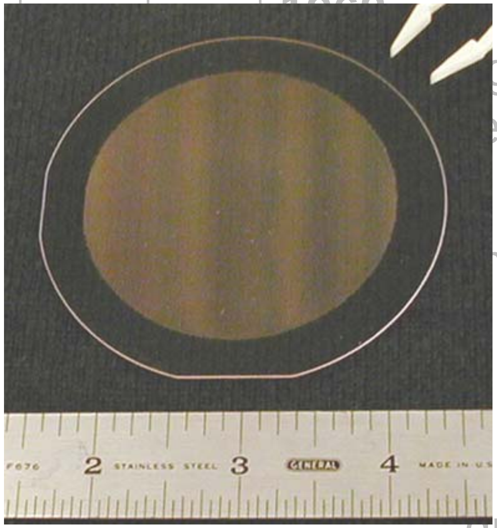
E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305

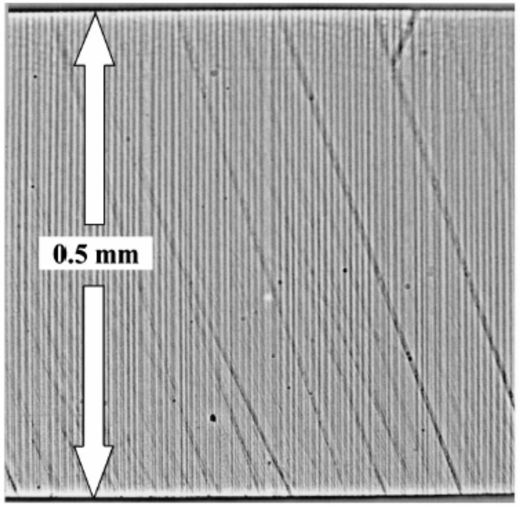
Theory of NLO

Diffusion poling

1997
Full wafer poling/visible

1960	1970	1980	1990





Template-Controlled Epitaxy of GaAs: 1995

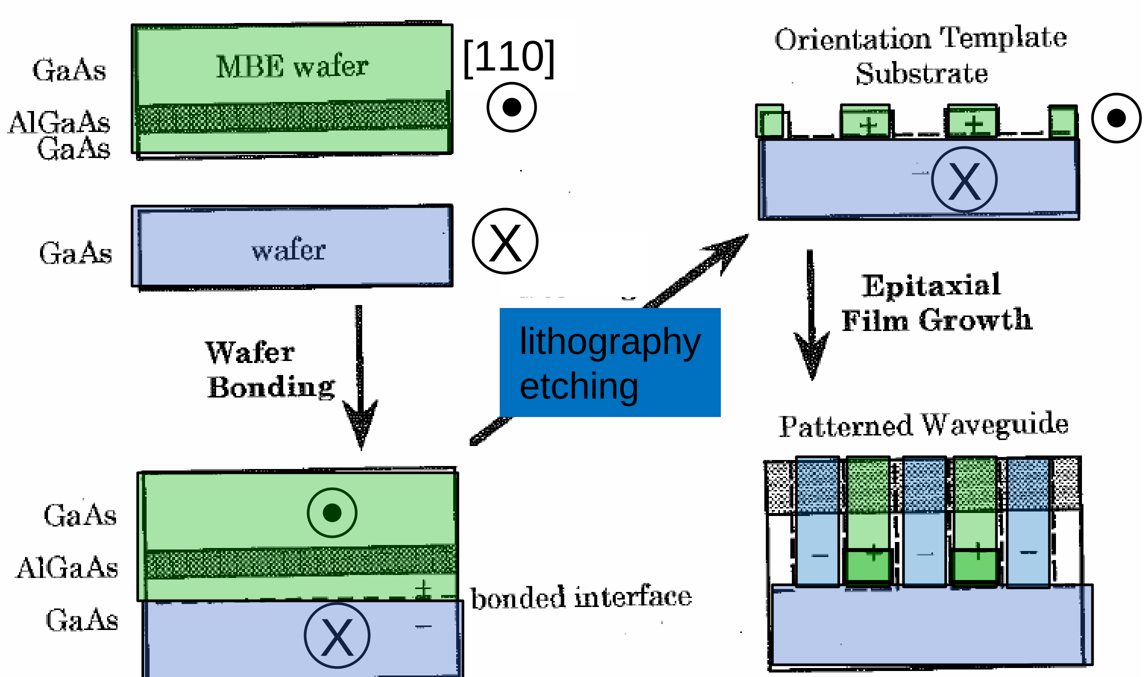
8:00-8:15pm
PD5
Quasi-Phasematched Second Harmonic Generation in AlGaAs Waveguides Prepared by Wafer-Bonding
S. J. B. Yoo, R. Bhat, C. Caneau, M. A. Koza, *Bell Communications Research*

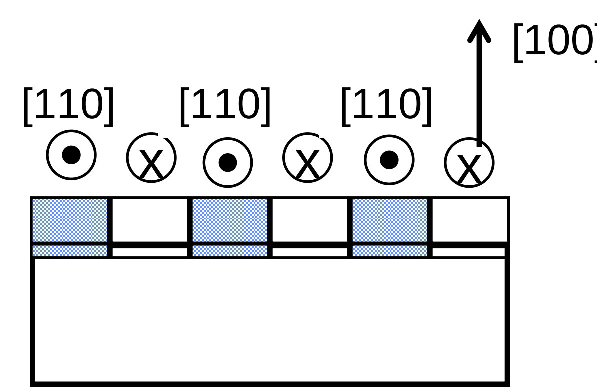
NLGWA
1995

4:15pm
NFC3 • Fabrication of GaAs orientation template substrates and growth of orientation-patterned GaAs thin films for quasi-phase-matched guided-wave nonlinear optics, Loren A. Eyres, Chris B. Ebert, James S. Harris, Jr., Martin M. Fejer, *Stanford Univ.;* Herman Chui, *Sandia National Laboratories.* Growth of GaAs thin films with

1995
Wafer-bonded-template QPM GaAs WGs

1960	1970	1980	1990	2000	2010





All-Epitaxial OP-GaAs Waveguides: 1999

1960
Maiman & ruby laser

1962
Bloembergen: Theory of NLO

1972
Twinned semicon

ELSEVIER

Journal of Crystal Growth 201/202 (1999) 187–193

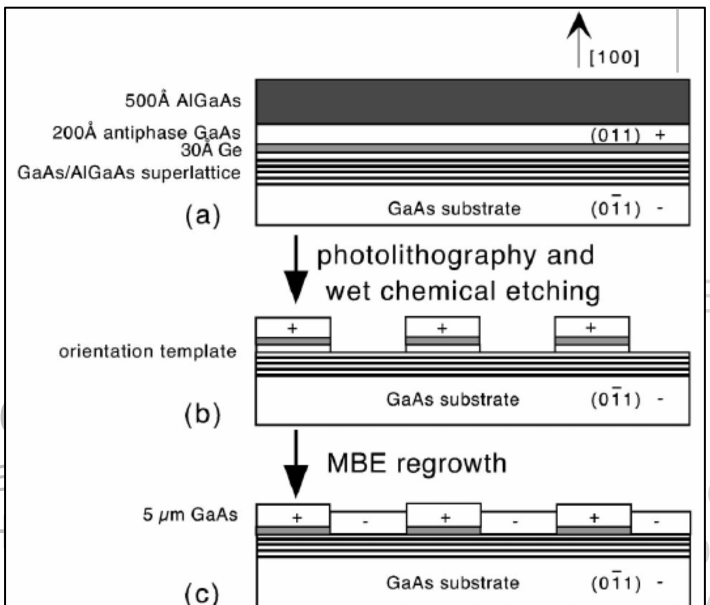
JOURNAL OF CRYSTAL GROWTH

MBE growth of antiphase GaAs films using GaAs/Ge/GaAs heteroepitaxy

Christopher B. Ebert, Loren A. Eyres, Martin M. Fejer, James S. Harris, Jr.*

Solid State and Photonics Laboratory, Stanford University, Stanford, CA, USA

1960	1970	1980	1990	2000	2010



E-beam poling

1992
E-field poling for waveguides

1999
Orientation-patterned GaAs WGs

1993
Diffusion-bonded GaAs

All-Epitaxial OP-GaAs Waveguides: 1999

1972

N·H

JOURNAL OF **CRYSTAL GROWTH**

Jpn. J. Appl. Phys. Vol. 38 (1999) pp. L 508–L 511
Part 2, No. 5A, 1 May 1999

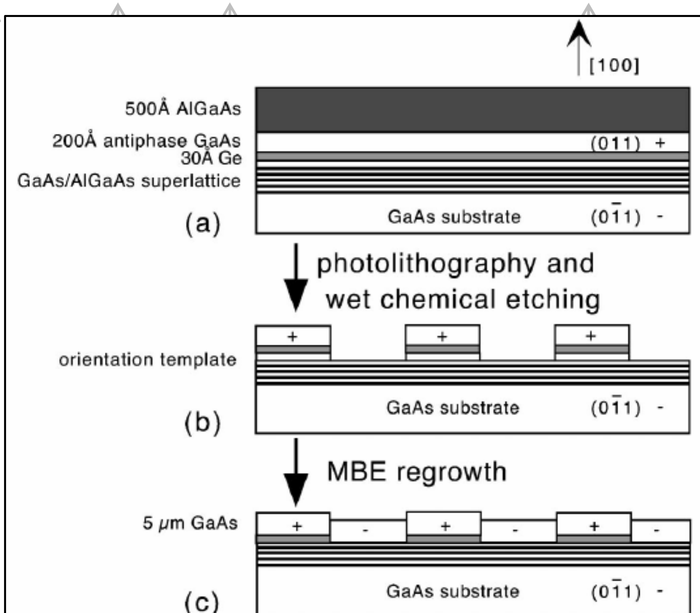
GaAs/Ge/GaAs Sublattice Reversal Epitaxy on GaAs (100) and (111) Substrates for Nonlinear Optical Devices

Shinji KOH*, Takashi KONDO[1], Minoru EBIHARA, Tetsuya ISHIWADA[1], Hidetaka SAWADA[1], Hideki ICHINOSE[1], Ichiro SHOJI and Ryoichi ITO
Department of Applied Physics, Faculty of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[1]*Department of Materials Science, Faculty of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

...using GaAs/Ge/GaAs

Christopher B. Ebert, Loren A. Eyres, Martin M. Fejer, James S. Harris, Jr.*
Solid State and Photonics Laboratory, Stanford University, Stanford, CA, USA

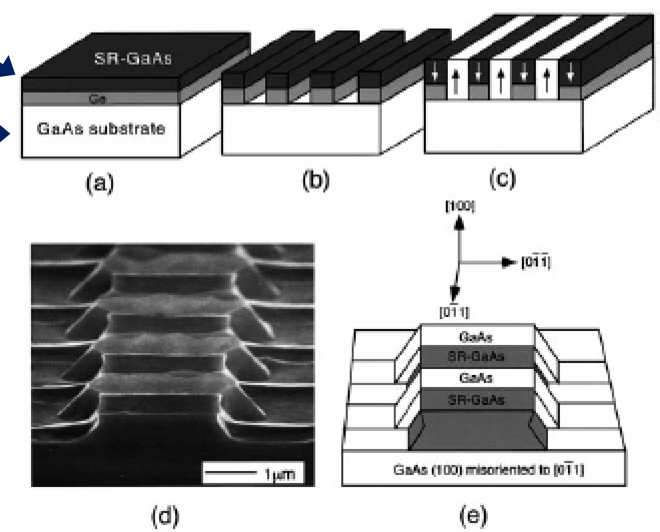
1960	1970	1980	1990	2000	2010



0̄11 GaAs
Ge
011 GaAs

E-beam
poling

1992
ume E-field
poling for
waveguides



Bulk OP-GaAs by HVPE on Orientation Templates: 2001

APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 7 13 AUGUST 2001

All-epitaxial fabrication of thick, orientation-patterned GaAs films for nonlinear optical frequency conversion

L. A. Eyres,[a] P. J. Tourreau,[b] T. J. Pinguet, C. B. Ebert,[c] J. S. Harris, and M. M. Fejer
Center for Nonlinear Optical Materials, Stanford University, Stanford, California 94305-4090

L. Becouarn,[d] B. Gerard, and E. Lallier
Laboratoire Central de Recherches, THALES, Domaine de Corbeville-91404 Orsay Cedex, France

(Received 19 February 2001; accepted for publication 12 June 2001)

1960 Maiman & ruby laser

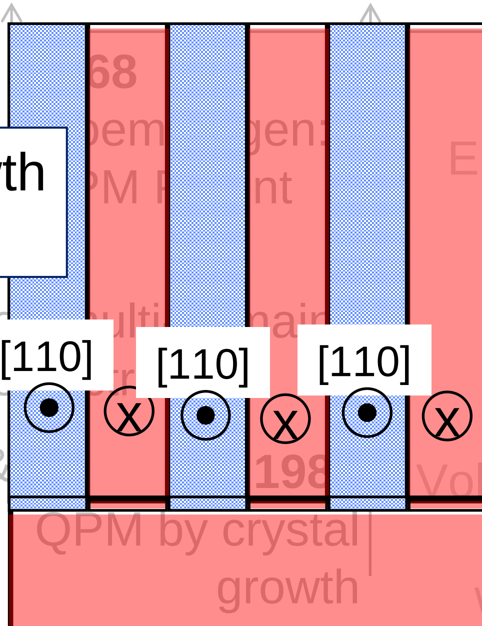
1961 Franken & SHG

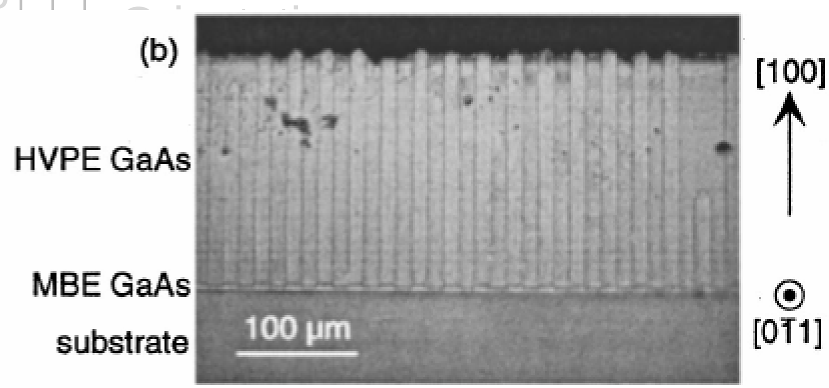
1991 Electric field poling

1960	1970	1980	1990	2000	2010

2001
OP-GaAs
thick films

high rate growth
HVPE





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APPLIED PHYSICS LETTERS VOLUME ... T 2001

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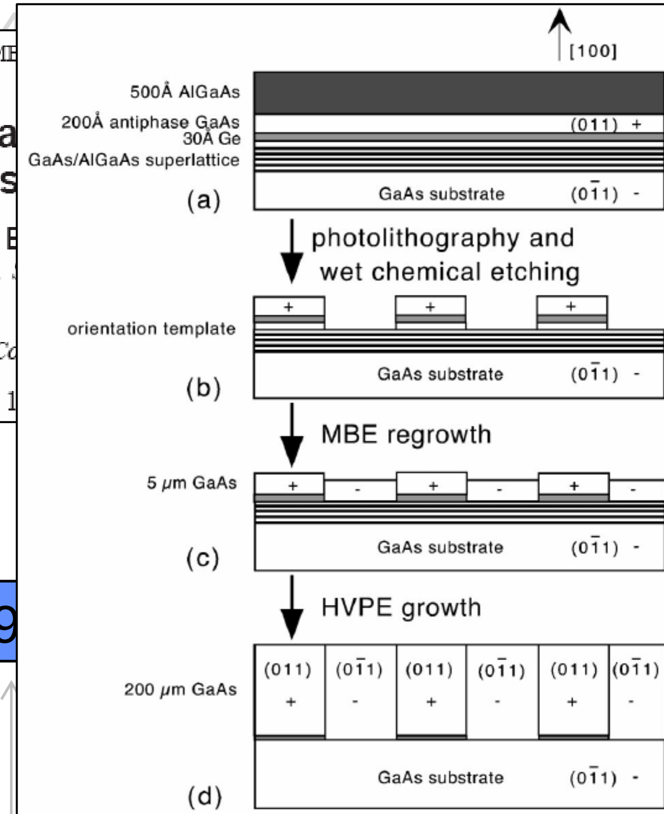


1960 Maiman & ruby laser

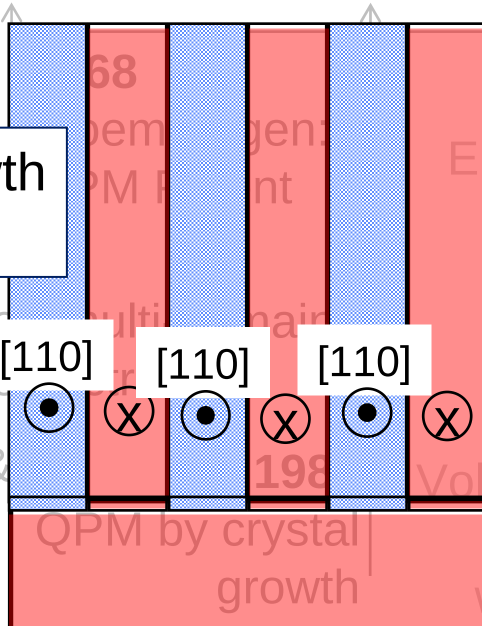
1962 Bloembe... Theory of NLO

1960 | 1970 | 1980 | 199...

... Diffusion poling

1961 Franken & SHG

high rate growth HVPE

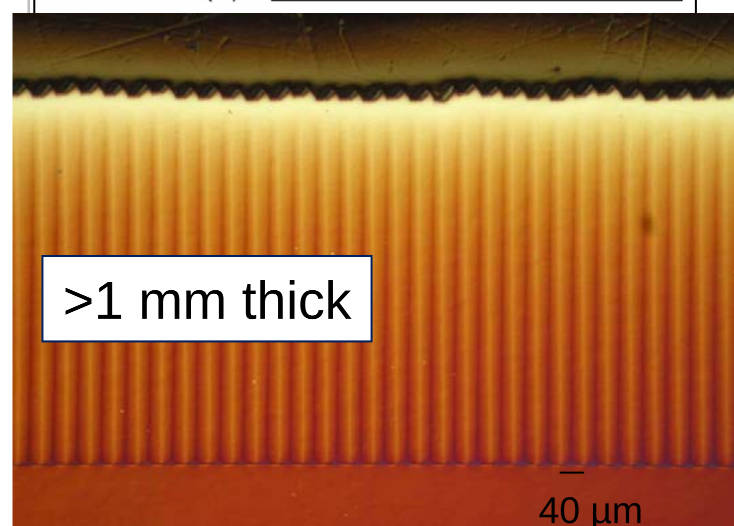


1991 Electric field poling

E-beam poling

1992 Volume E-field poling for waveguides

... QPM by crystal growth



First QPM OP-GaAs OPO: 2004

1912 OPTICS LETTERS / Vol. 29, No. 16 / August 15, 2004

Optical parametric oscillation in quasi-phase-matched GaAs

K. L. Vodopyanov, O. Levi, P. S. Kuo, T. J. Pinguet, J. S. Harris, and M. M. Fejer

E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305

B. Gerard, L. Becouarn, and E. Lallier

Thales Research & Technology, F-91404 Orsay, France

2004
OP-GaAs
OPO

poling

1960	1970	1980	1990	2000	2010

1968
Bloembergen:
QPM Patent

1964
Miller: multi-domain
ferroelectrics

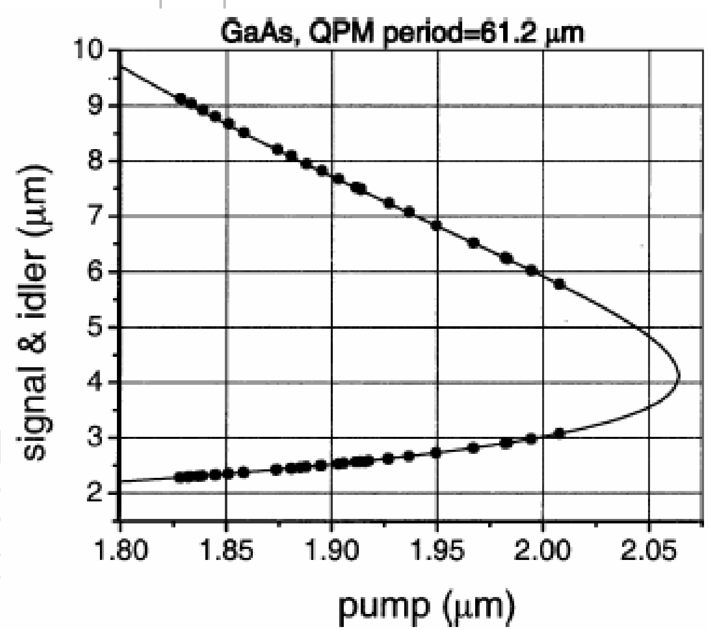
1961
Franken &
SHG

1980
QPM by crystal
growth

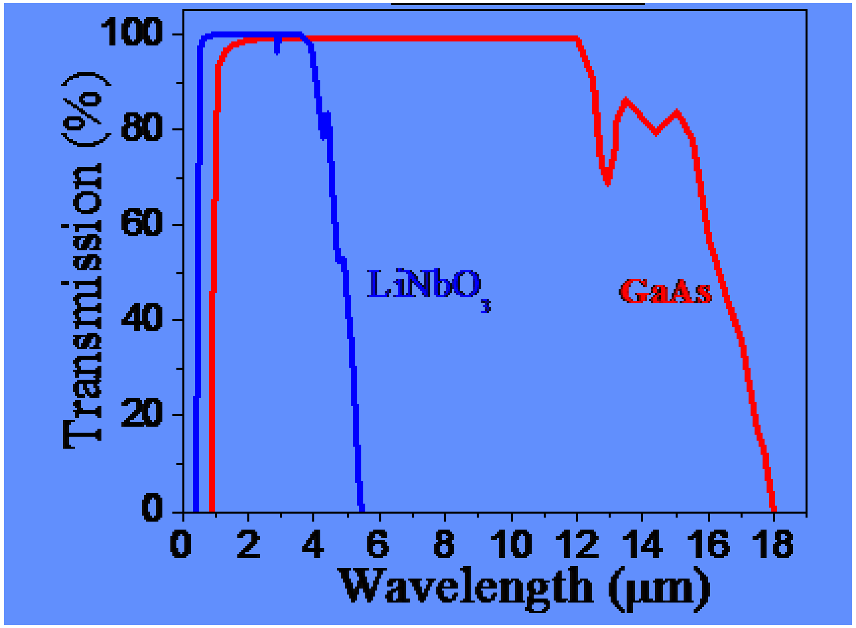
1991
Electric field
poling

E-beam
poling

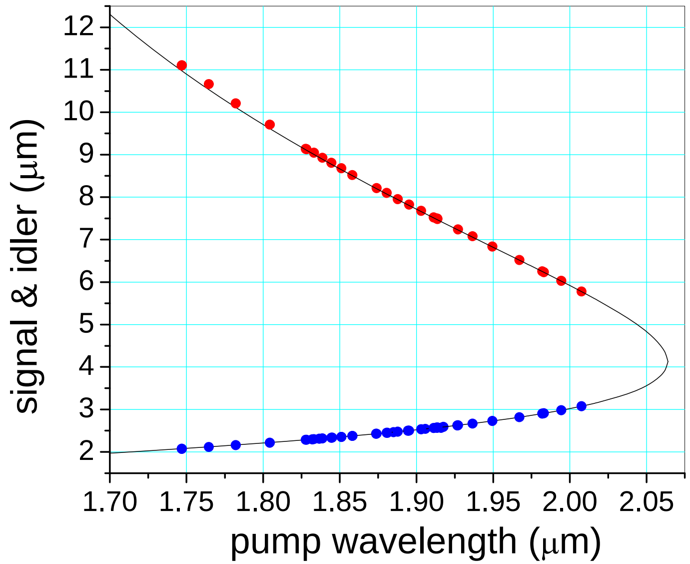
1992
Volume E-field
poling for
waveguides



Materials: Orientation-Patterned GaAs for mid-IR QPM

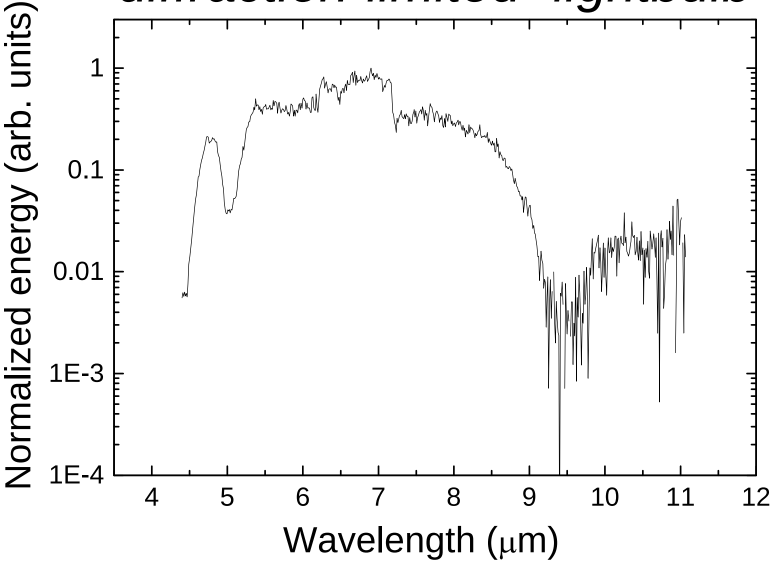


OPO operating 2.1 – 11 μm

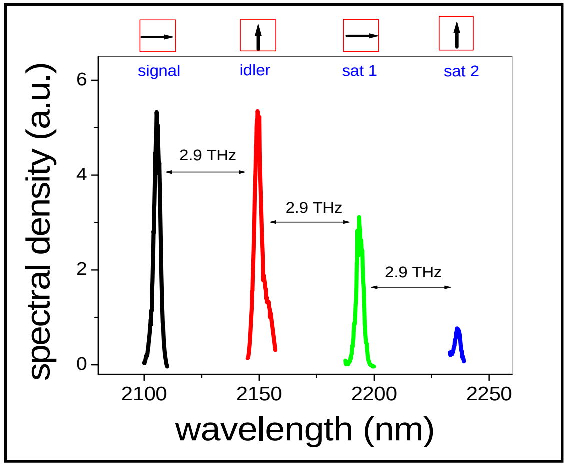


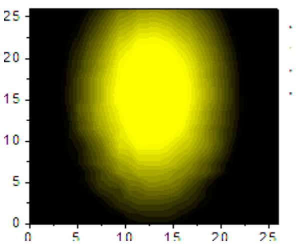
Octave bandwidth OPG: 4.5 – 11 μm

diffraction-limited "lightbulb"



4% QE, 1 mW avg THz Generation



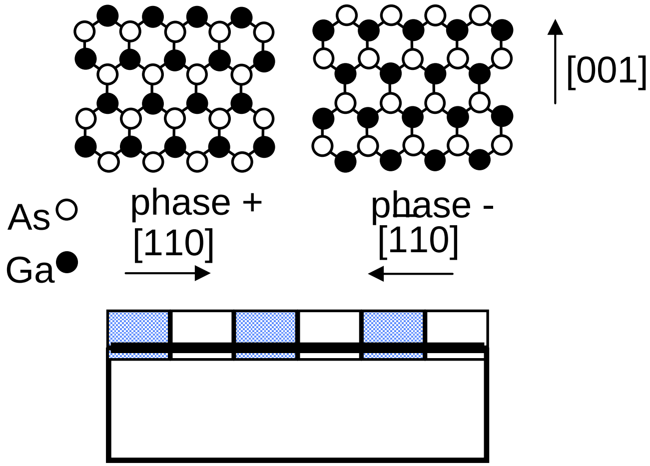


Diffraction-limited THz beam

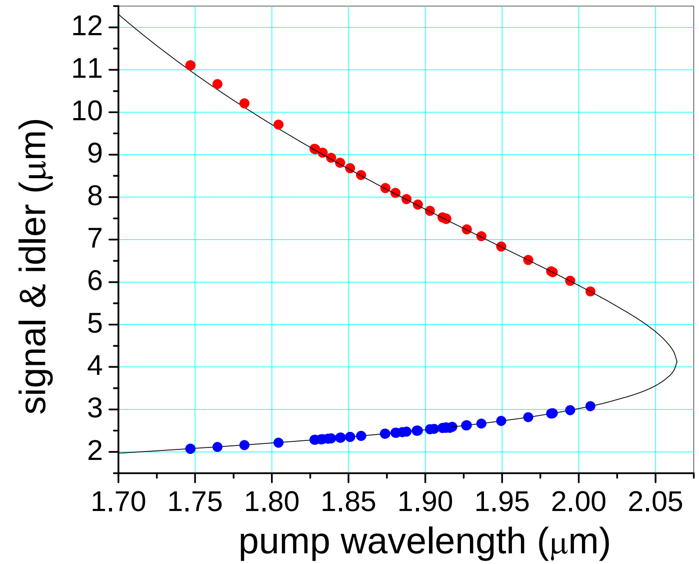
THz cascading: beat Manley-Rowe limit?

Materials: Orientation-Patterned GaAs for mid-IR QPM

$\bar{4}3m$: 90° rotation produces inversion

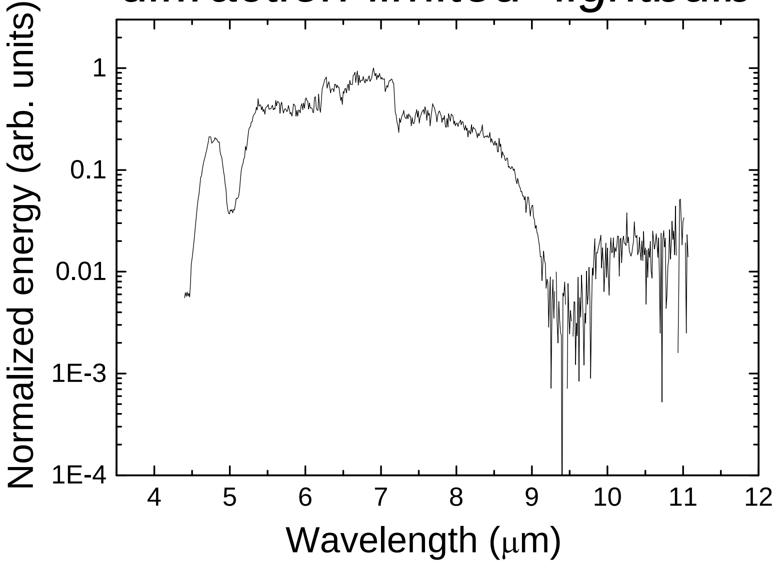


OPO operating 2.1 – 11 μm



Octave bandwidth OPG: 4.5 – 11 μm

diffraction-limited "lightbulb"



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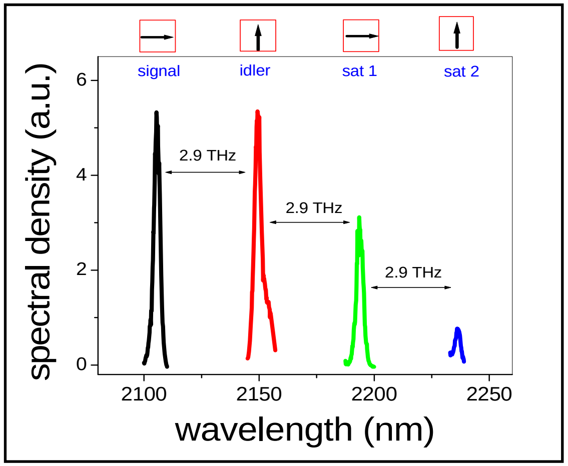
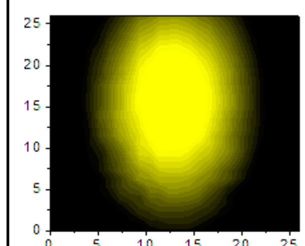


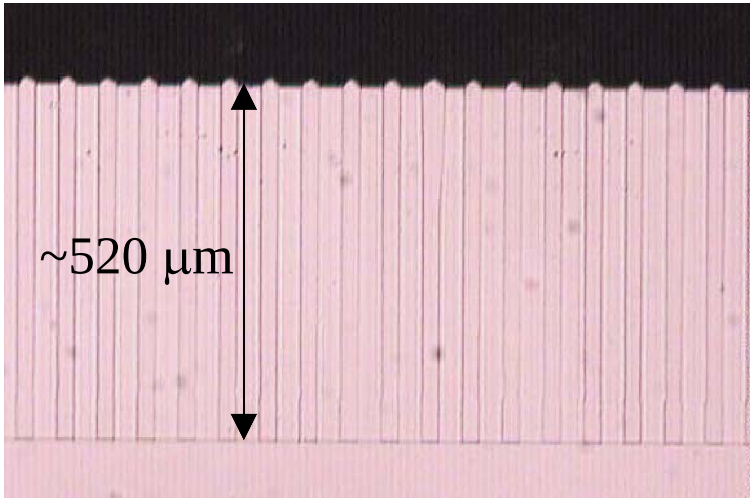
THz cascading: beat Manley-Rowe limit?



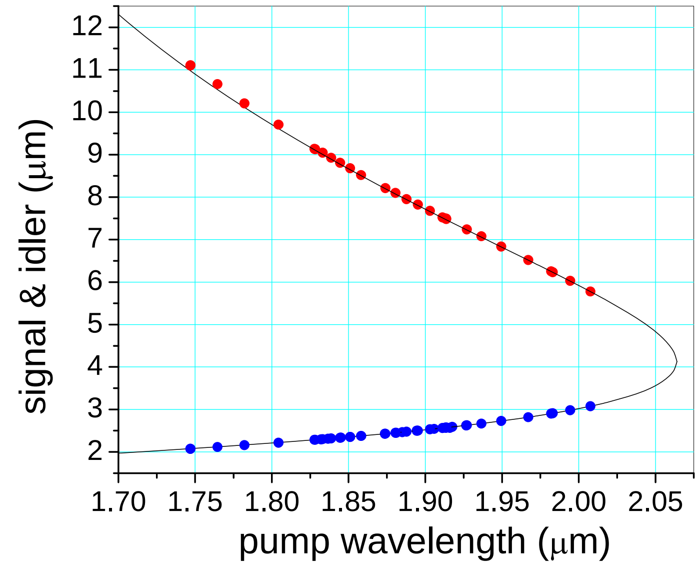
Diffraction-limited THz beam

Materials: Orientation-Patterned GaAs for mid-IR QPM

MBE template and HVPE thick film

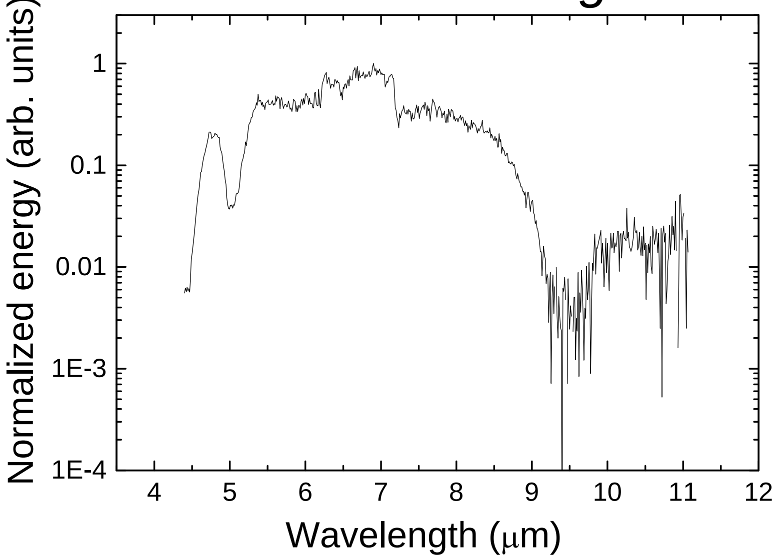


OPO operating 2.1 – 11 μm

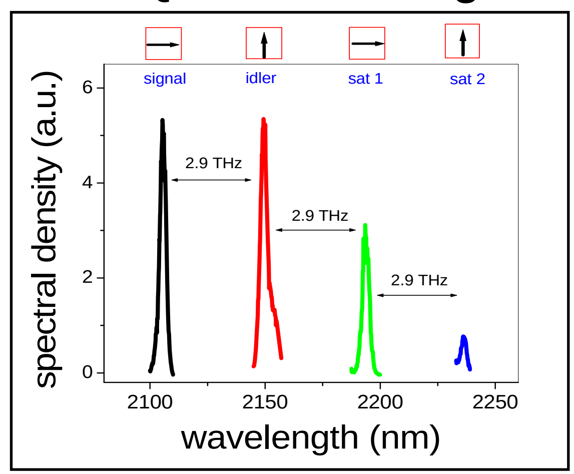


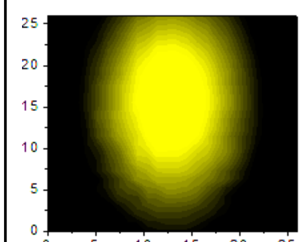
Octave bandwidth OPG: 4.5 – 11 μm

diffraction-limited "lightbulb"



4% QE, 1 mW avg THz Generation

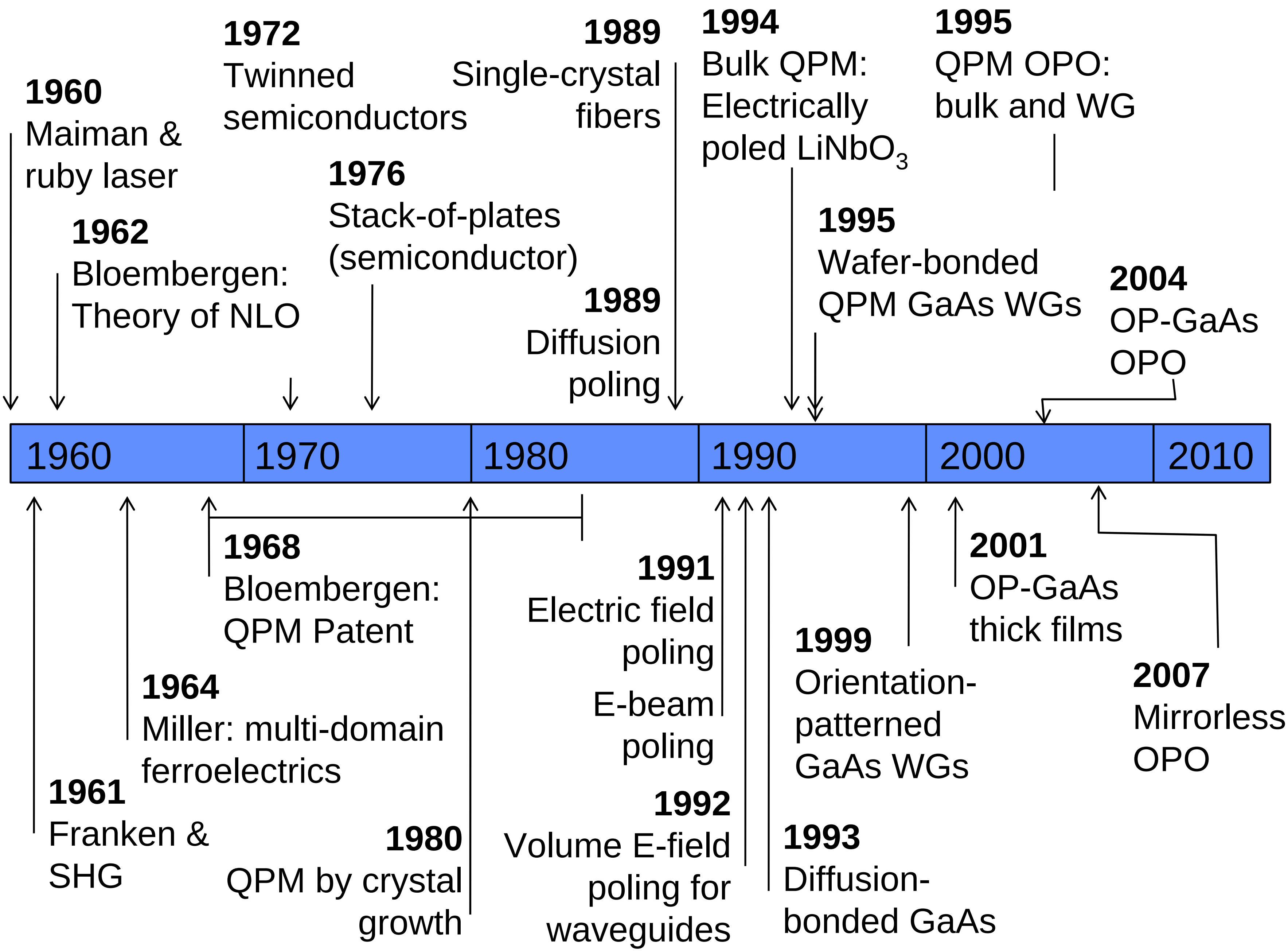




Diffraction-limited THz beam

THz cascading: beat Manley-Rowe limit?

Mirrorless Counterpropagating OPO: 2007



Summary

- NLO 50 years old

- QPM 35 years old

- Rich history of materials and device concepts

- Significant developments ongoing
  - improved materials
    - oxides: peak and average power extension
    - semiconductors: mid-IR/THz wavelength extension
  - aperiodic QPM gratings
    - bandwidth enhancement
    - group delay manipulation
    - engineered trajectory of cascade nonlinearities: comb generation
  - quantum frequency conversion
    - single/few-photon devices
  - …

L.N. Durvasula: DARPA/CNOM
H. Schlossberg: AFOSR