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WINTER COLLEGE ON
LASER PHYSICS: SEMICONDUCTOR LASERS
AND INTEGRATED OPTICS

(22 February - 11 March 1988)

NON LINEAR INTEGRATED OPTICS

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Recent developments of integrated optical frequency conversion devices.

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University -GH Paderborn, Fed. Rep. Germany
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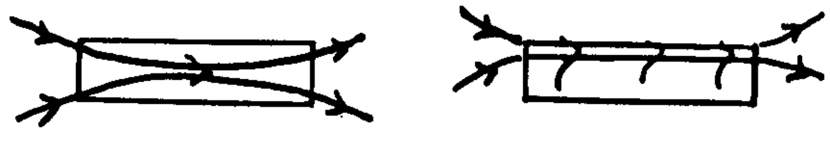
1) Nonlinear optical waveguides
2) Resonant second harmonic generator
3) Difference frequency generator
4) Optical parametric oscillator

SPIE - conference
Cannes: Nov. 1987 on
"Optoelectronics ..."

Adventages of nonlinear integrated optics:

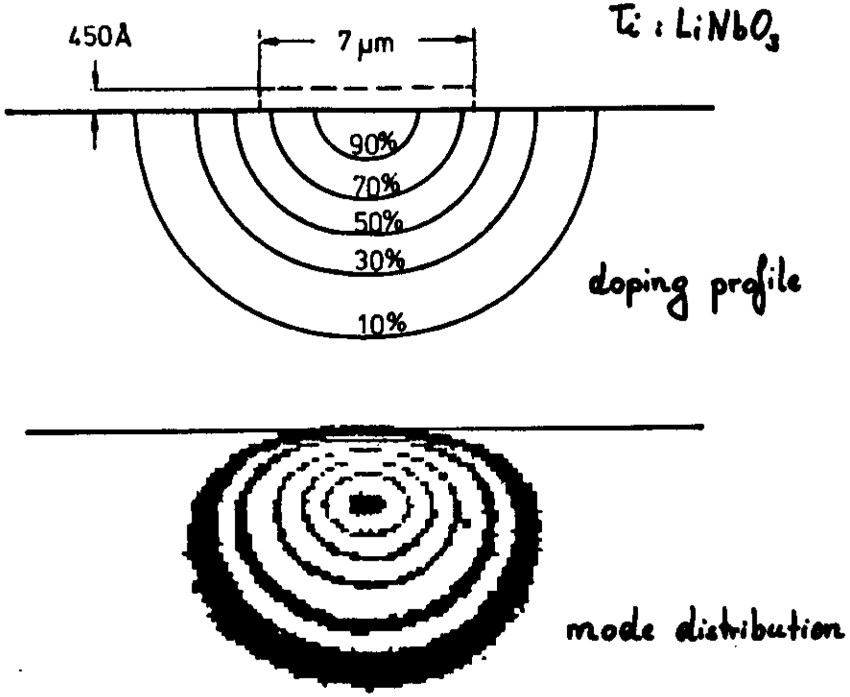
- high intensity over the whole interaction length

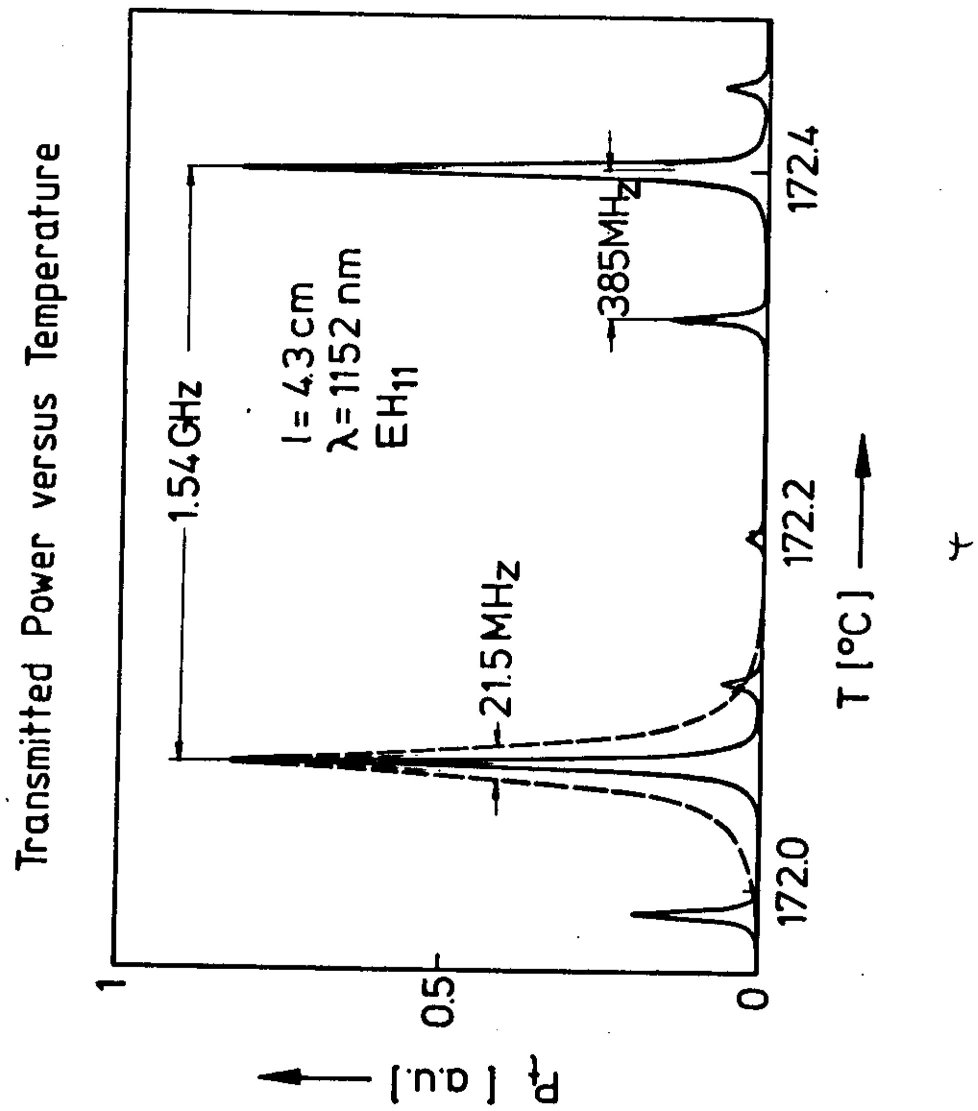


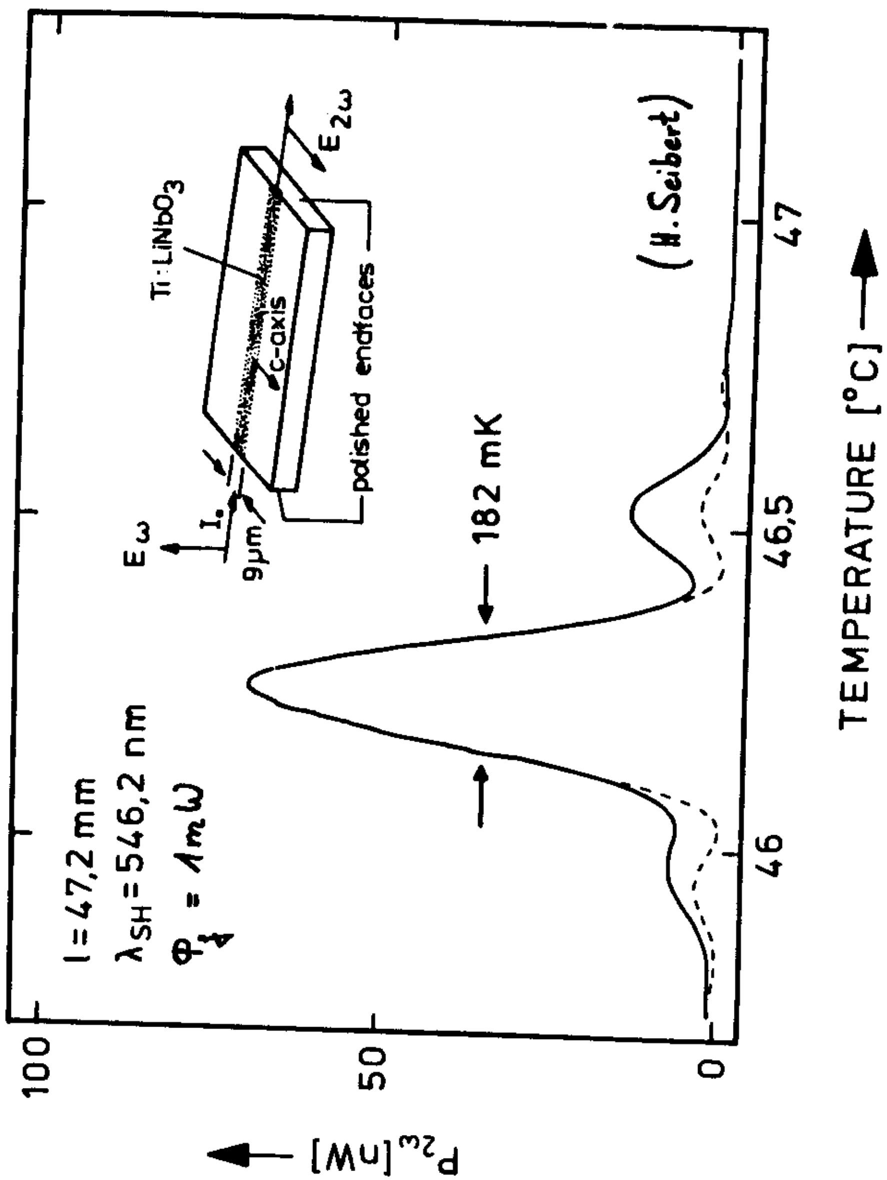
bulk optics   integrated optics

- highly efficient nonlinear interactions
- phase matching in isotropic materials
- compact, stable devices (e.g. resonators)
- low threshold of active devices like a parametric oscillator

1) Nonlinear optical waveguides

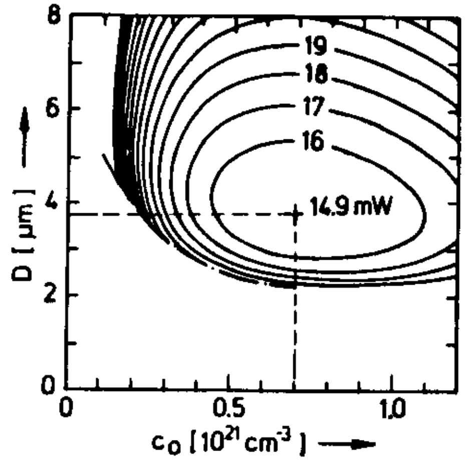




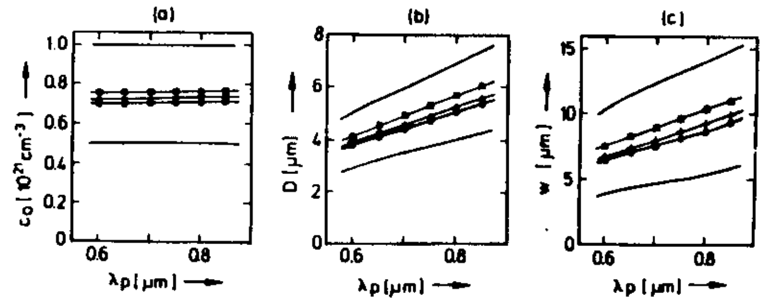


Modeling: Threshold pump power of IOPO:

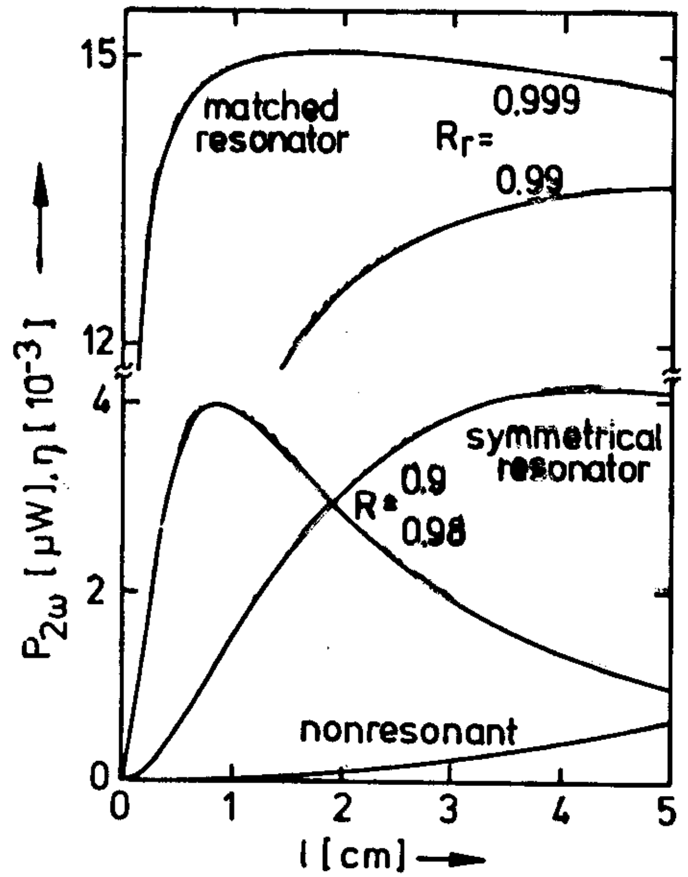
$$\varphi_p^{th} = f\left(\alpha, L, R_1, R_2, \int E_{\omega_p} E_{\omega_s} E_{\omega_i}\, dx\, dy\right)$$



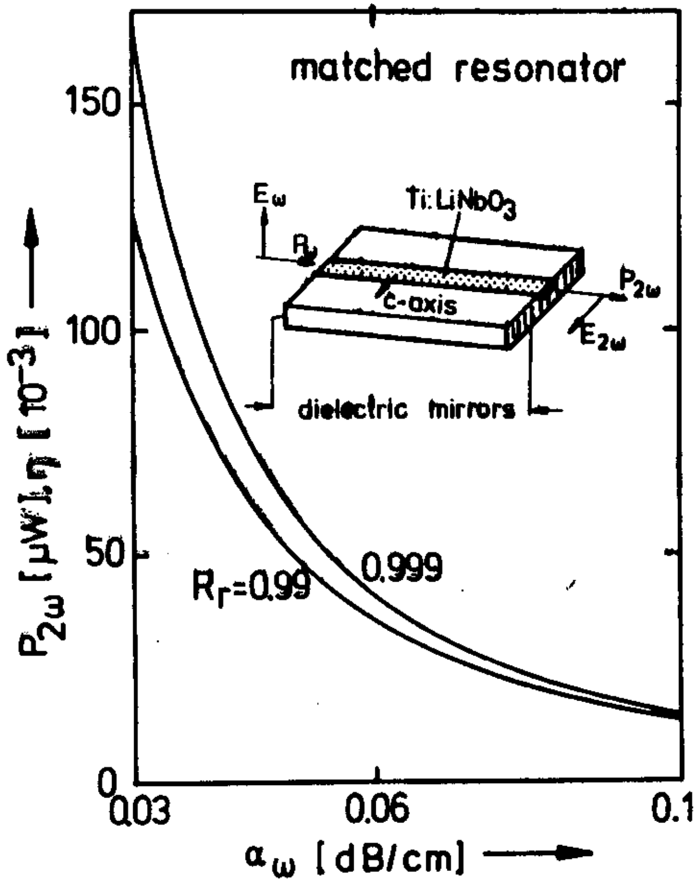
(G. Bava, I. Montrosset + ..)



2) Resonant second harmonic generator

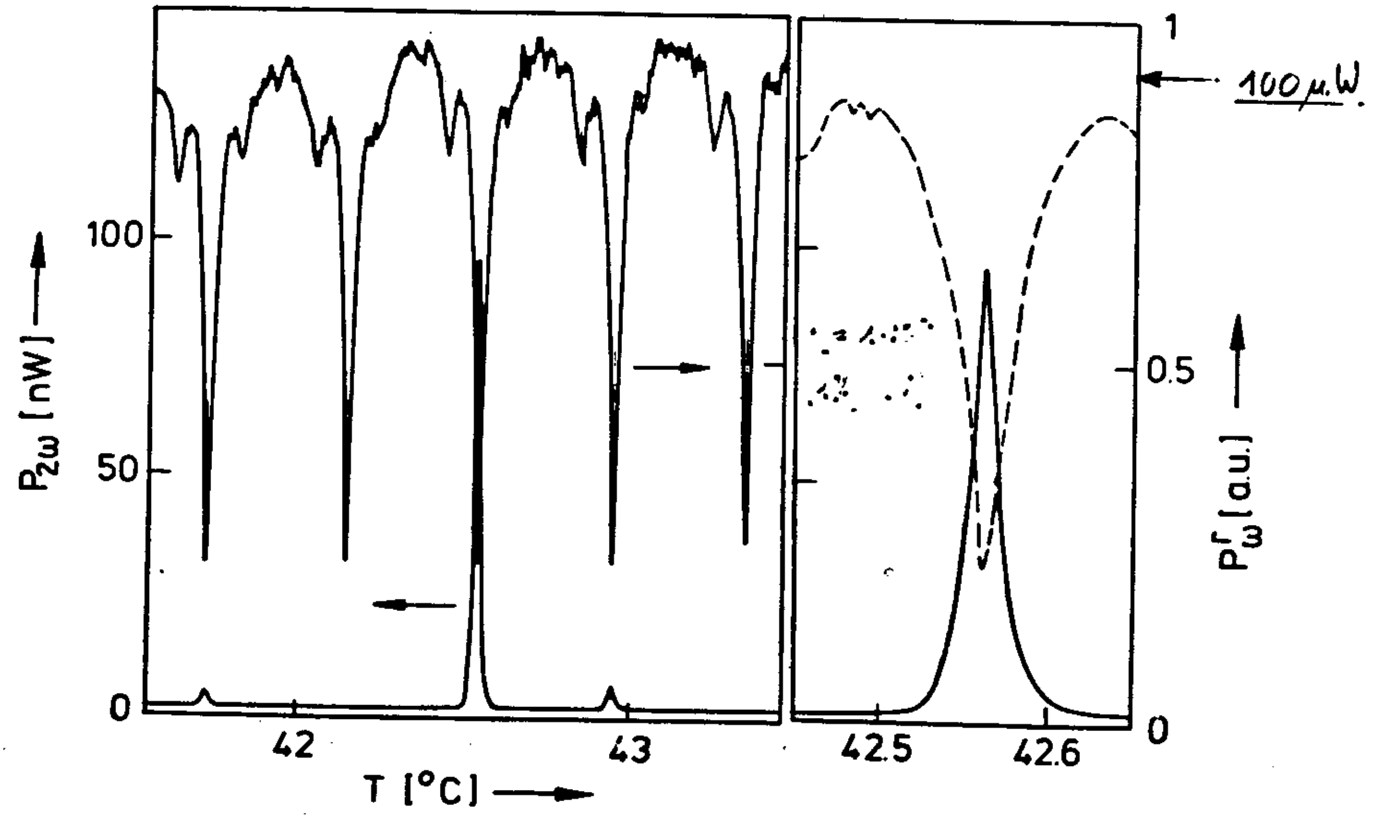


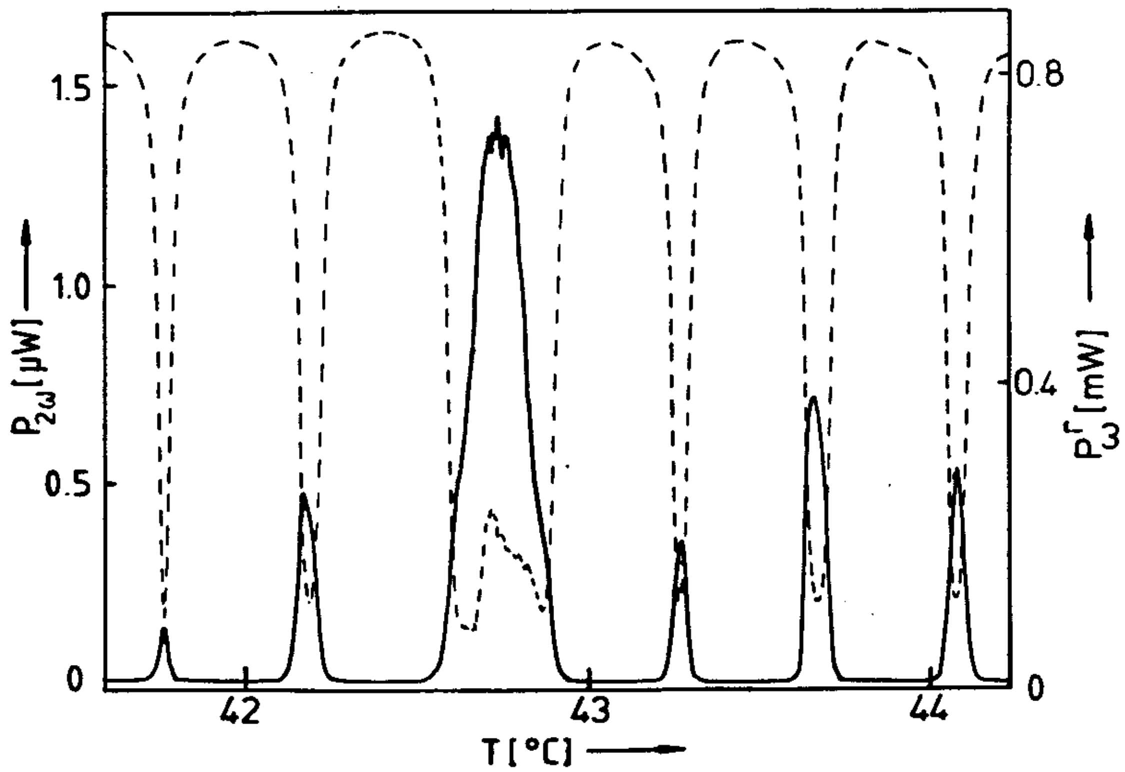
(R. Regener)

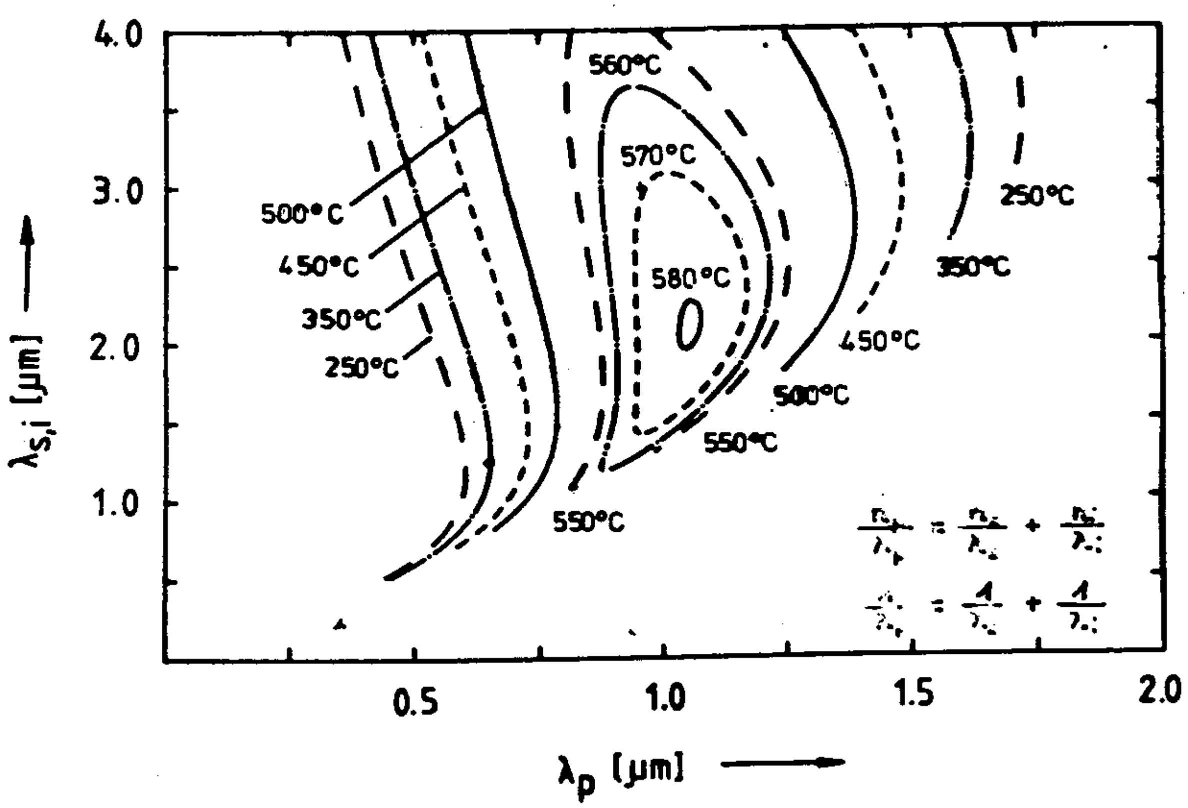


Second Harmonic and Reflected Fundamental Power versus Temperature

$\lambda_f = 1.09\ \mu m$







(H. Herrmann)

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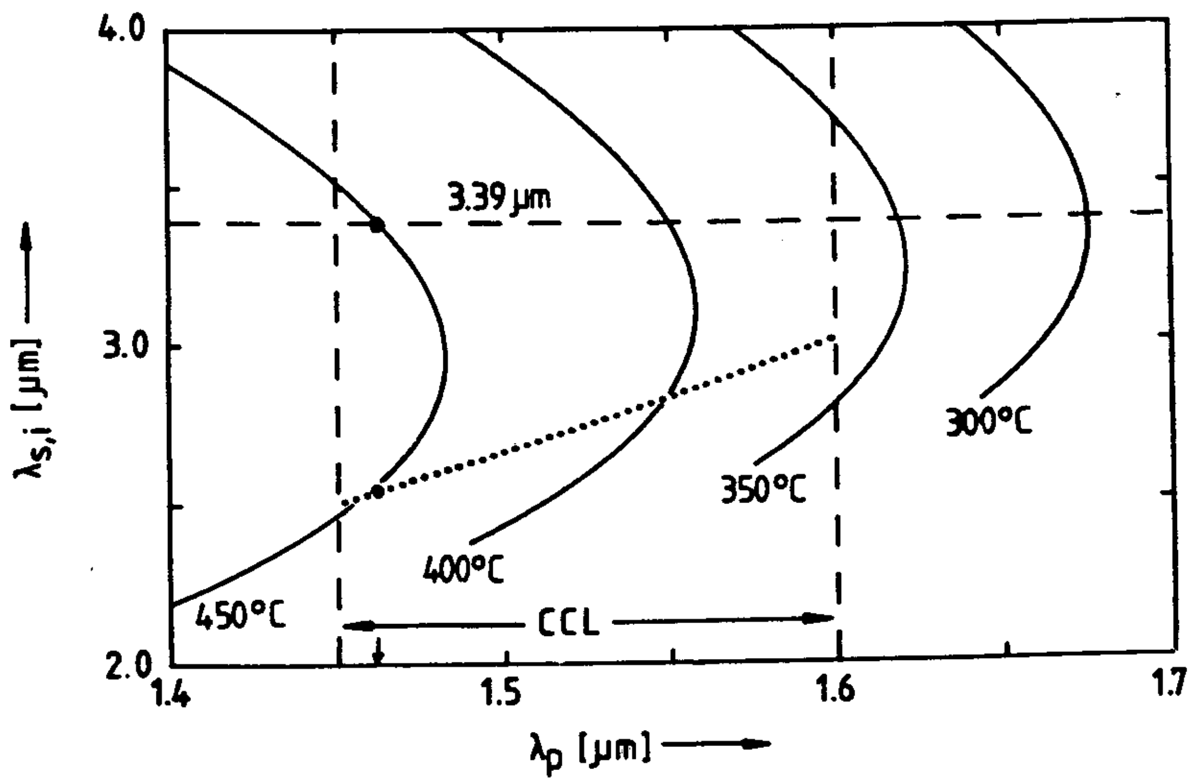

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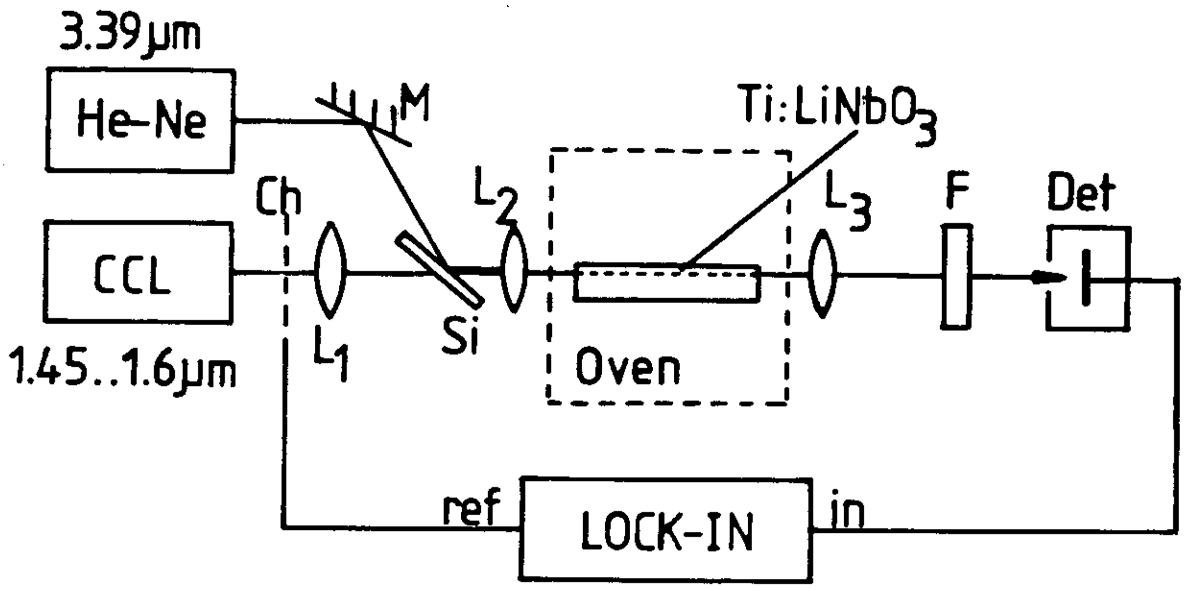
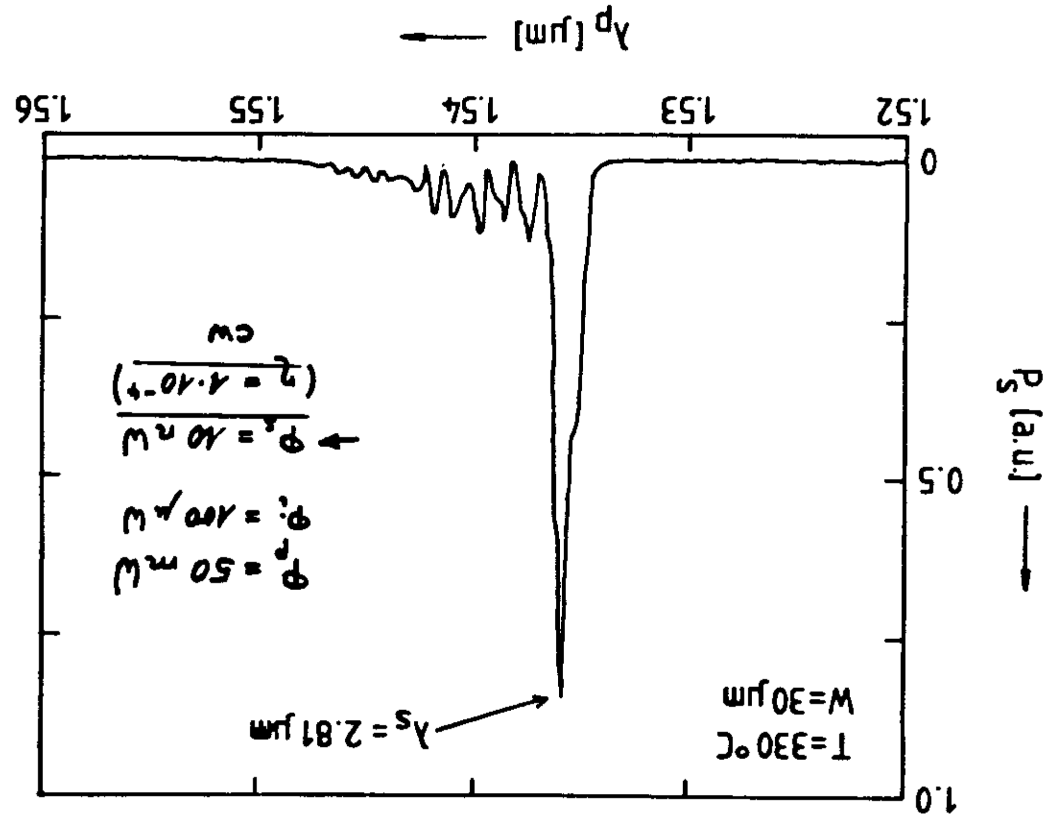
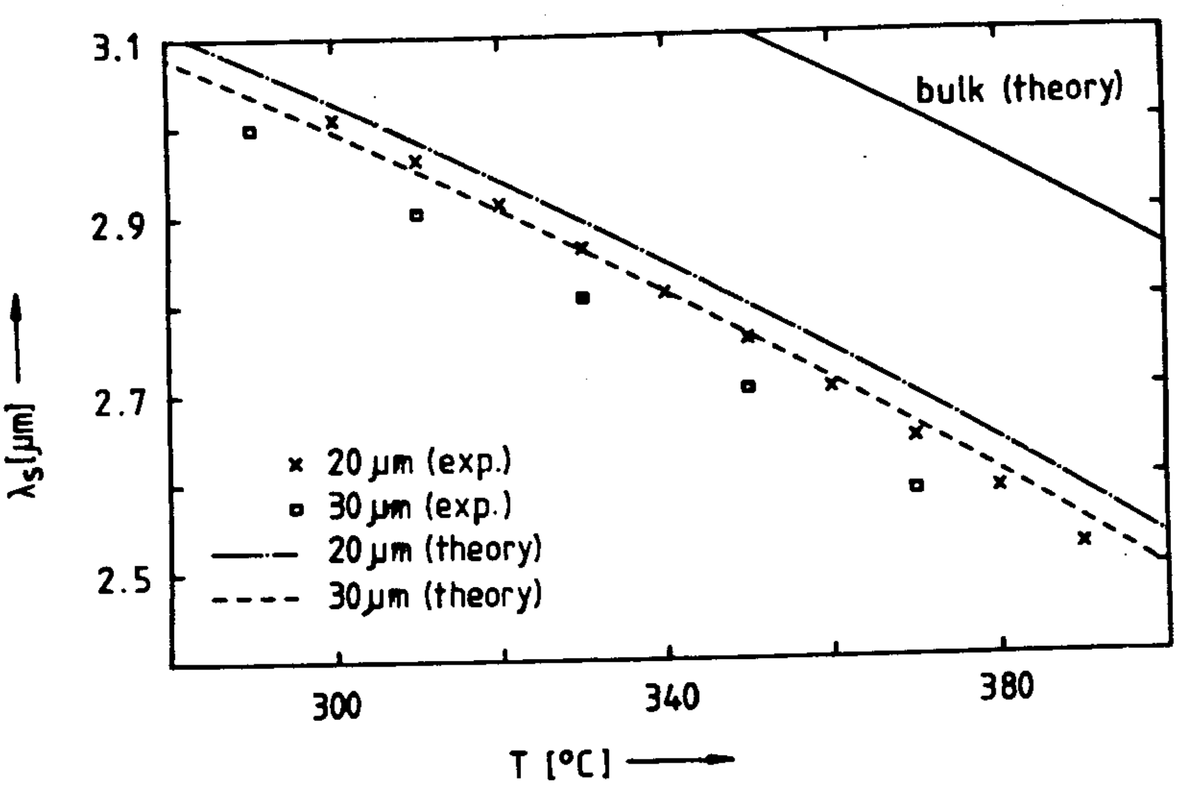

3.39μm
He-Ne
M
CCL
1.45..1.6μm
Ch
L1
Si
L2
Ti:LiNbO3
L3
F
Det
Oven
ref
LOCK-IN
in

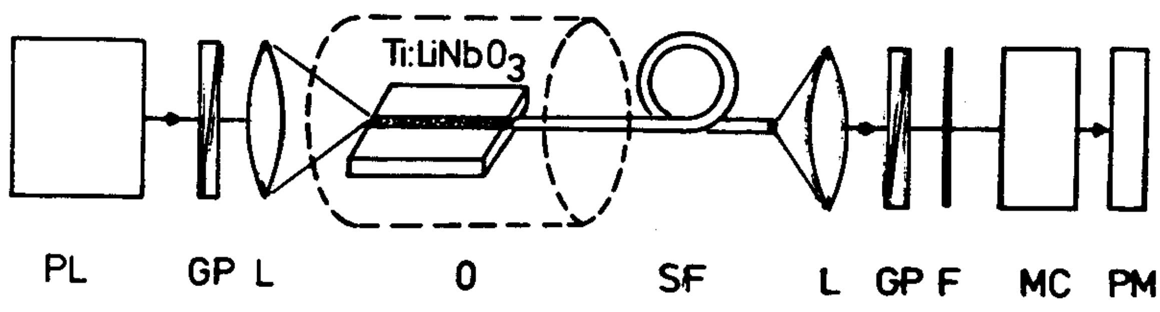
13

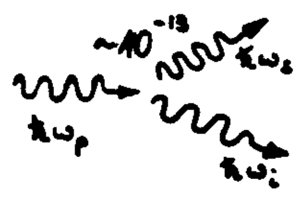

λp [μm]
1.52
1.53
1.54
1.55
1.56
Ps [a.u.]
0
0.5
1.0
T=330°C
W=30μm
λs = 2.81 μm
Φp = 50 mW
Φi = 100 μW
Φs = 10 nW
(η = 1·10^-4)
cw



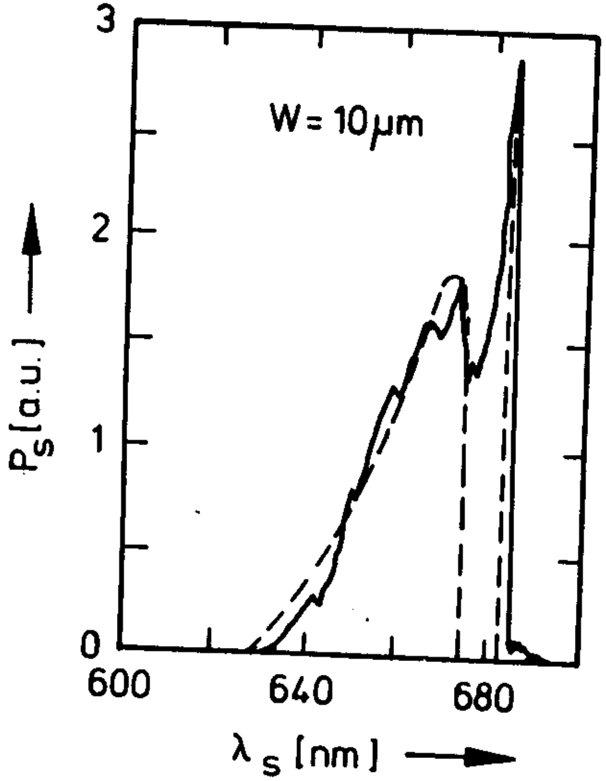
4) Optical parametric oscillator

a) Spontaneous parametric fluorescence:



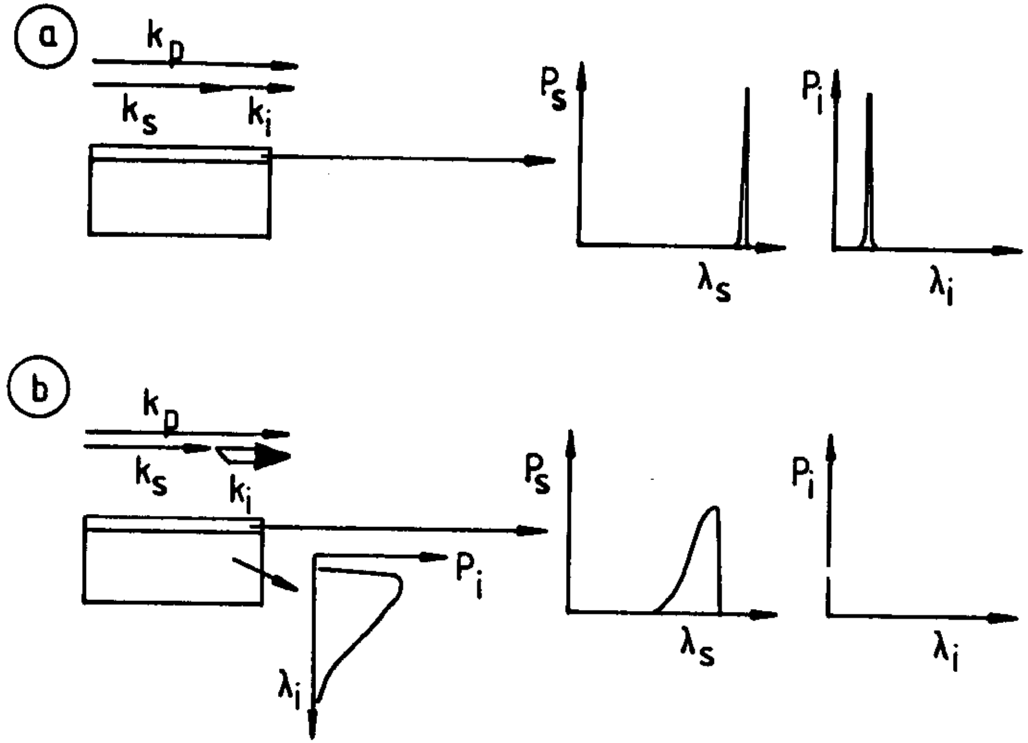


(B. Hampel)



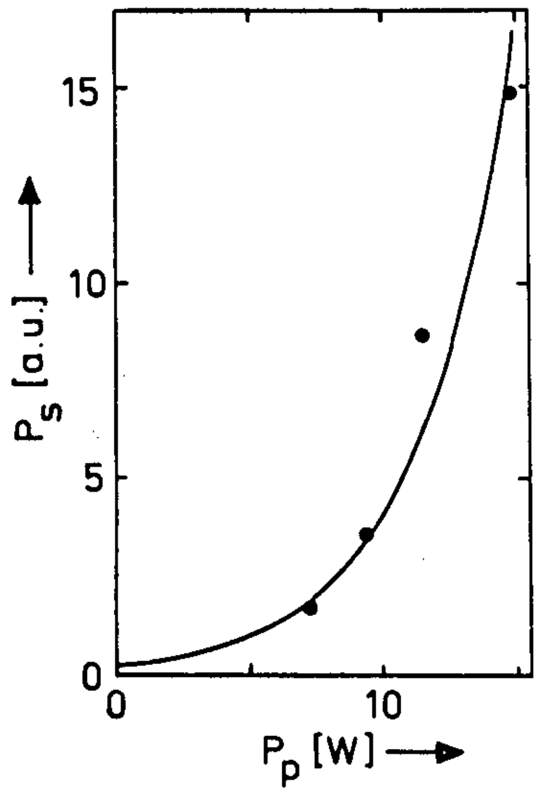
W = 10μm
3
2
1
0
600
640
680
P_s [a.u.]
λ_s [nm]

17

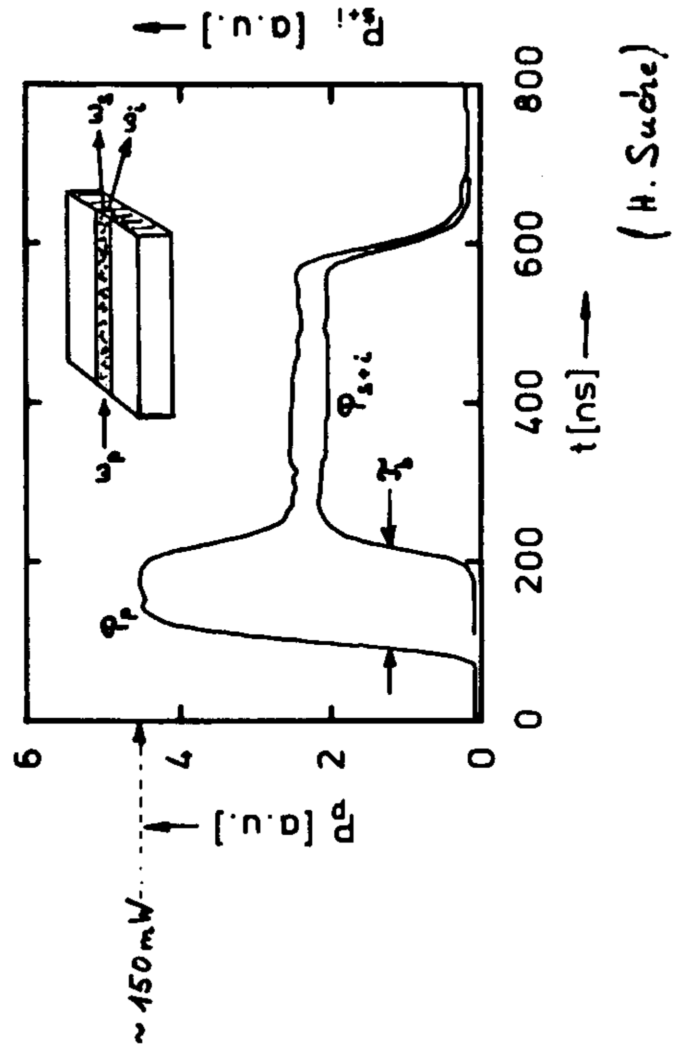


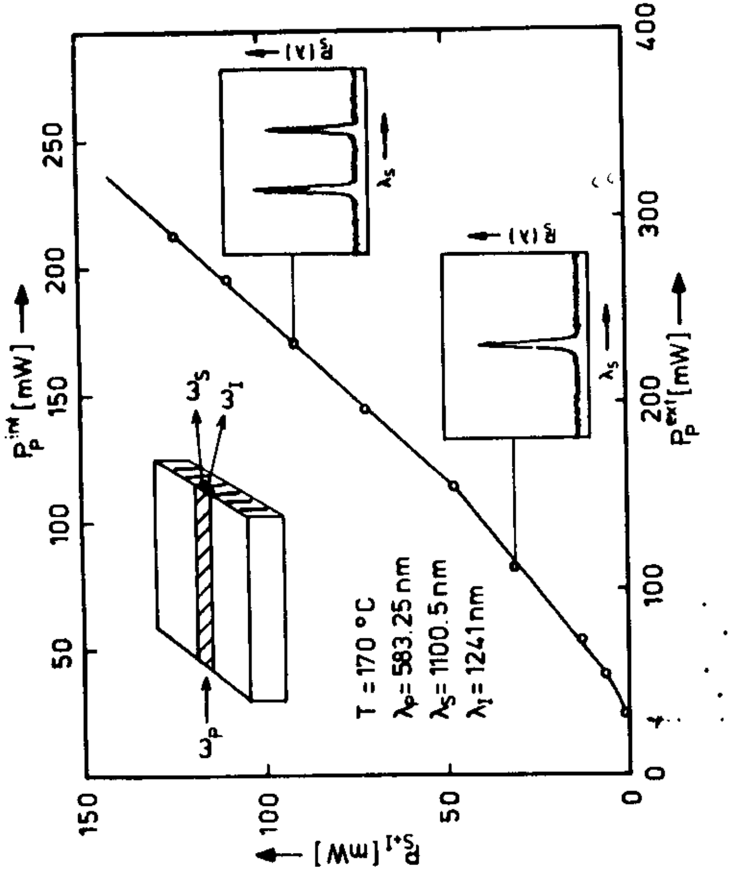
a
k_p
k_s
k_i
P_s
λ_s
P_i
λ_i
b
k_p
k_s
k_i
P_i
λ_i
P_s
λ_s
P_i
λ_i

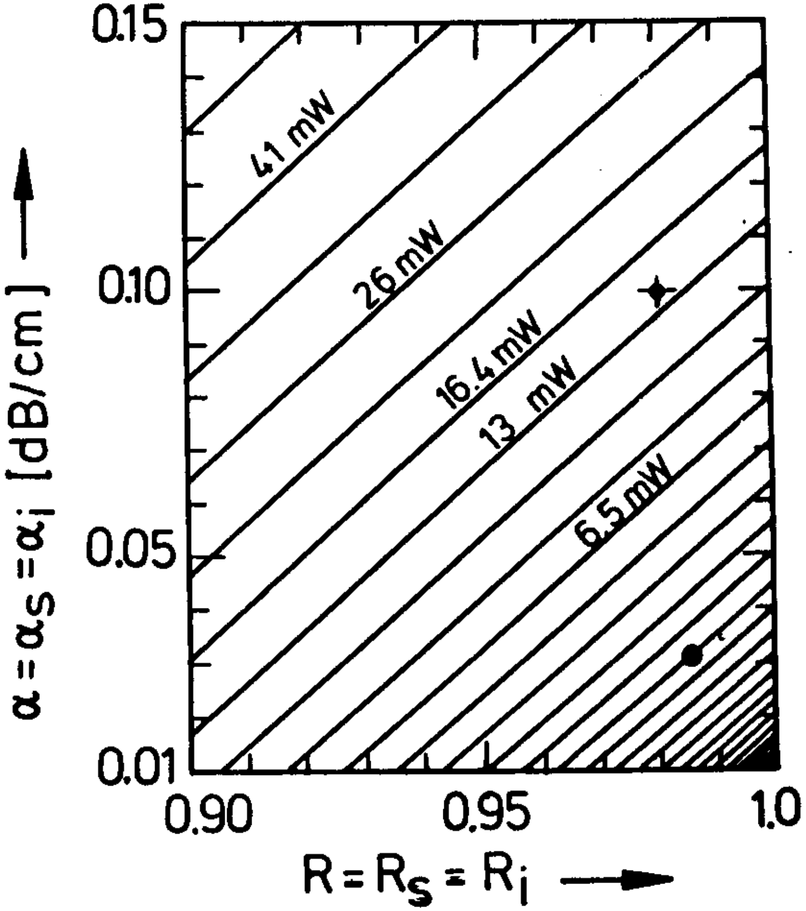
18



b) Power characteristics

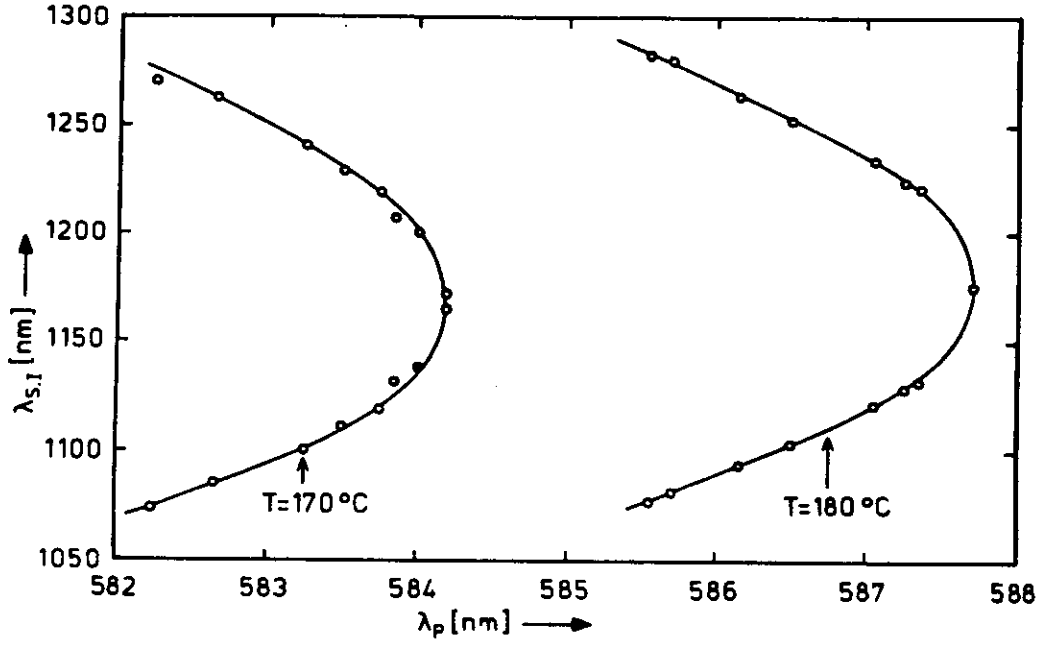






(G. P. Bava, I. Montrosset)

c) Spectral properties



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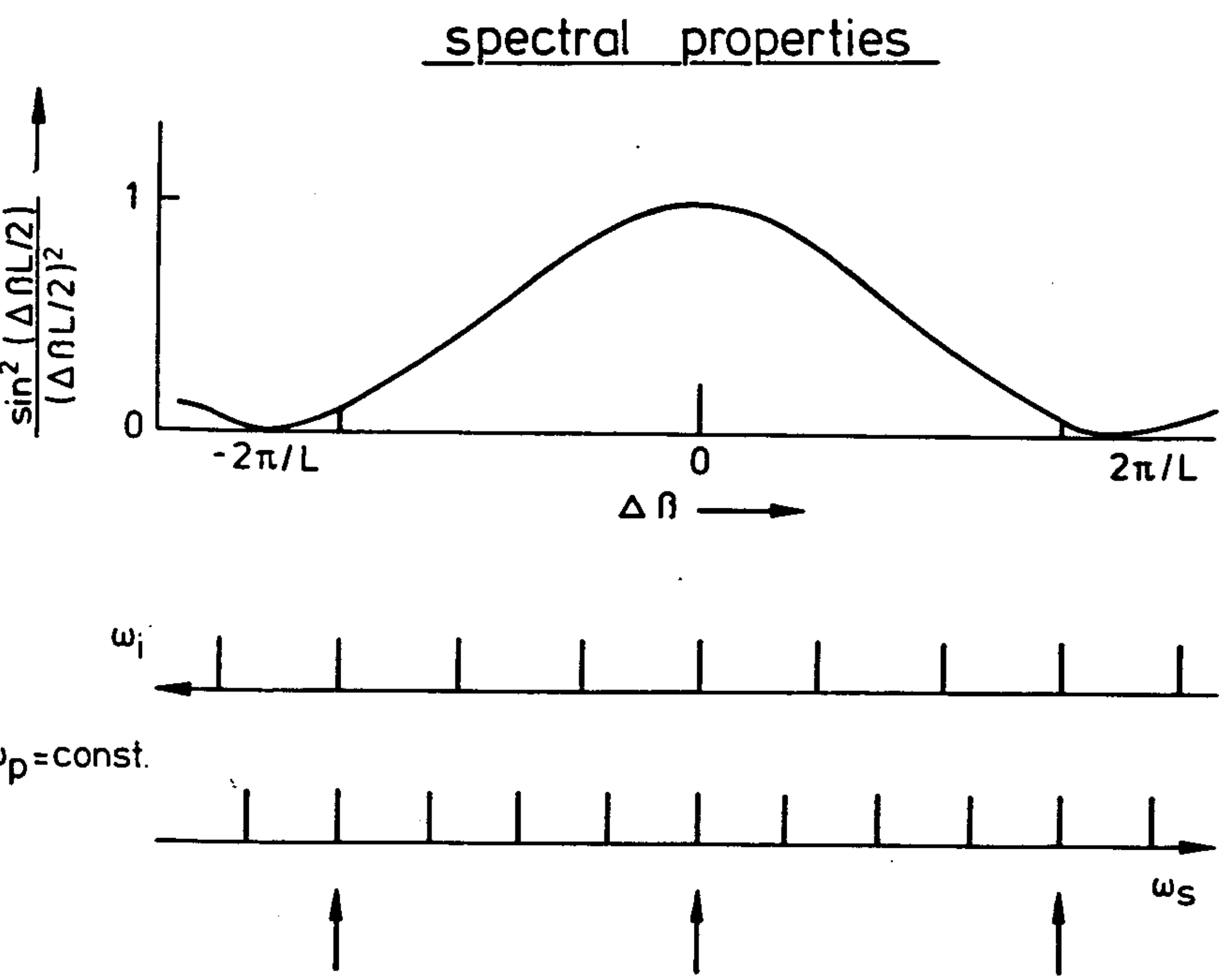

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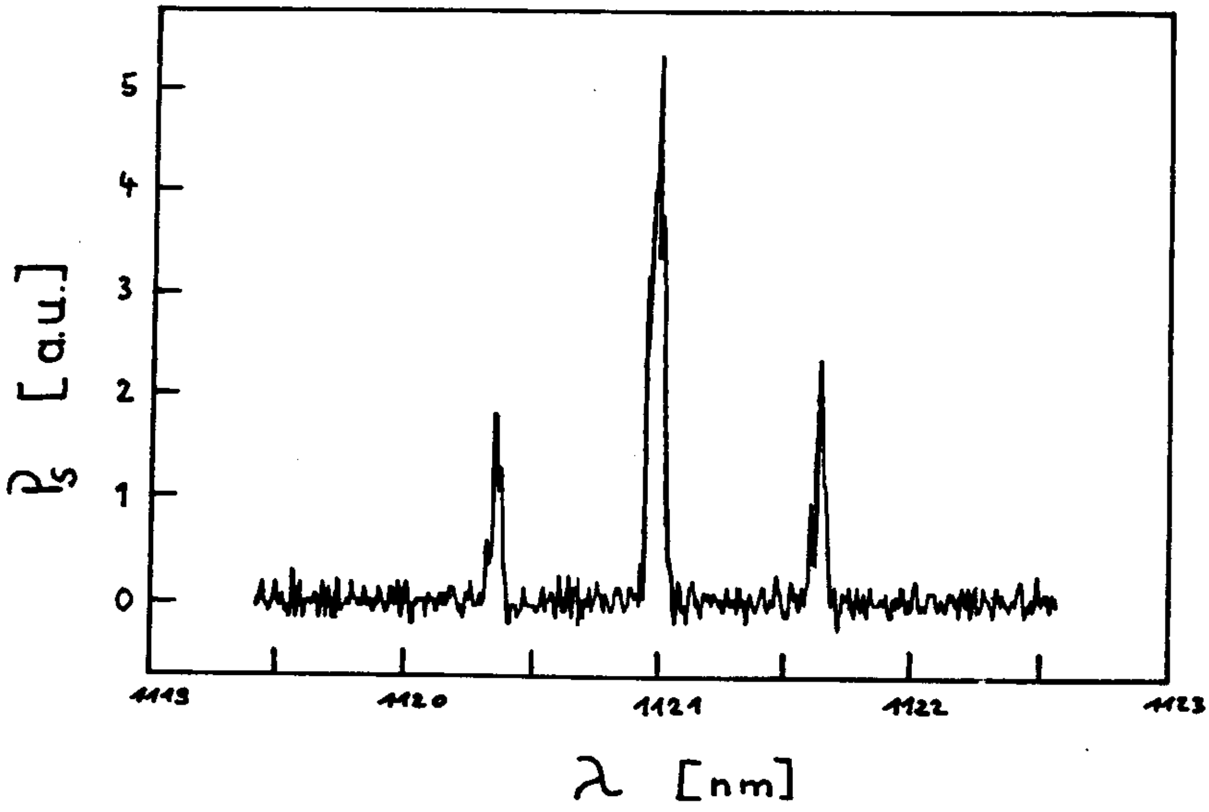

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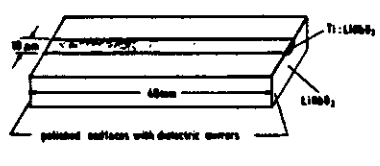
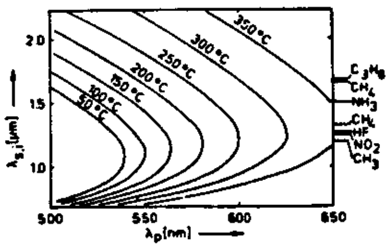
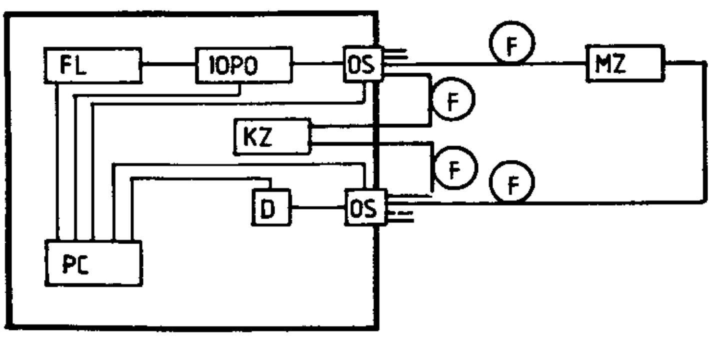
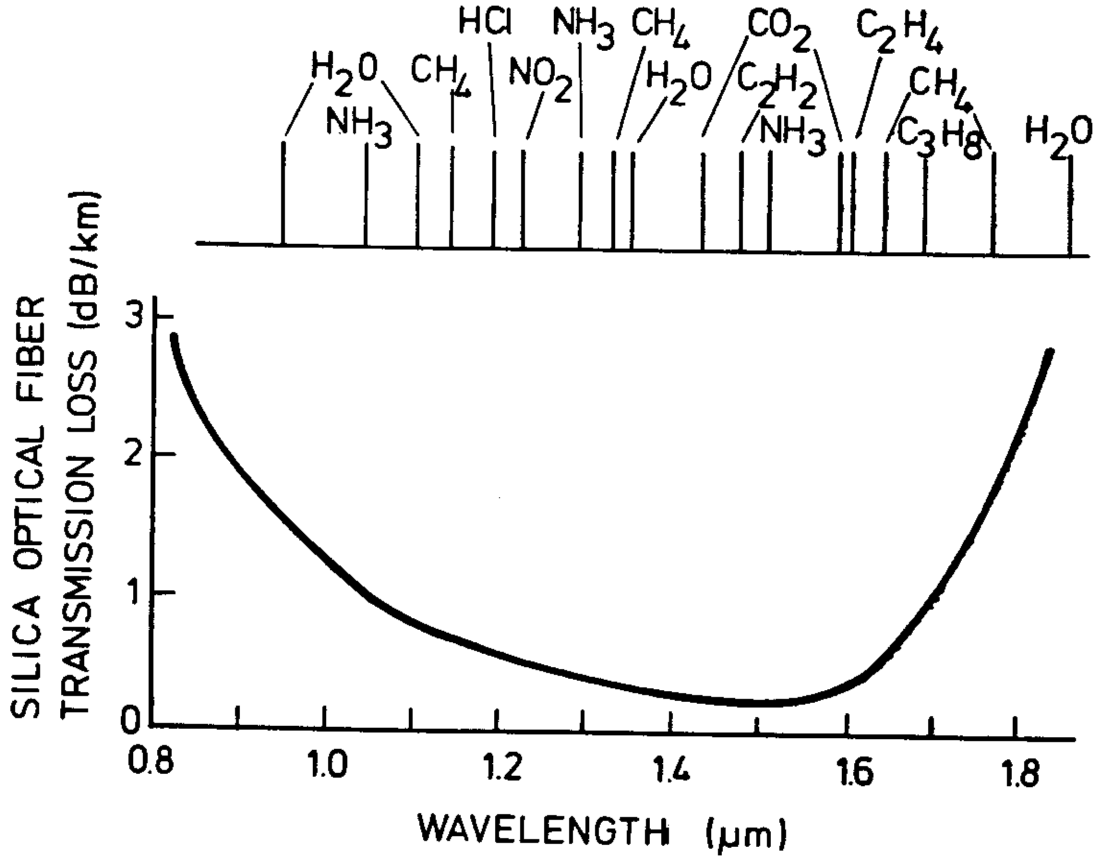
d) Applications:

Integriert optisches / faseroptisches Gasanalysesystem

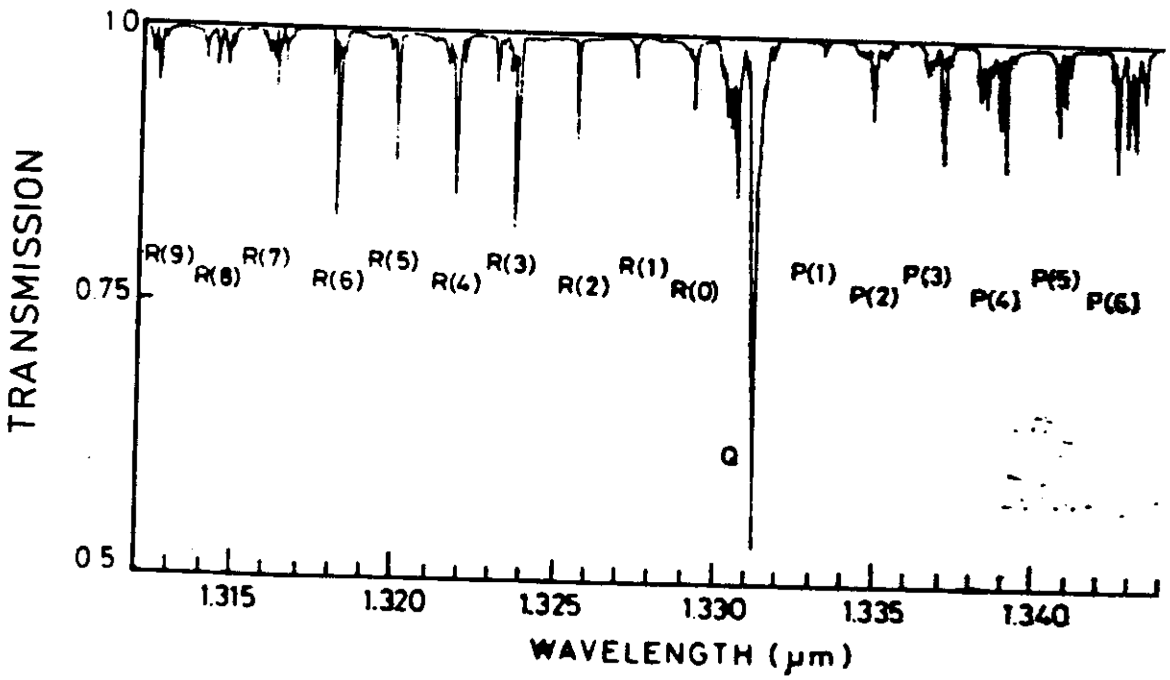







H2O
NH3
CH4
HCl
NO2
NH3
CH4
H2O
CO2
C2H2
NH3
C2H4
CH4
C3H8
H2O
SILICA OPTICAL FIBER
TRANSMISSION LOSS (dB/km)
3
2
1
0
0.8
1.0
1.2
1.4
1.6
1.8
WAVELENGTH (μm)

27


TRANSMISSION
1.0
0.75
0.5
R(9)
R(8)
R(7)
R(6)
R(5)
R(4)
R(3)
R(2)
R(1)
R(0)
Q
P(1)
P(2)
P(3)
P(4)
P(5)
P(6)
1.315
1.320
1.325
1.330
1.335
1.340
WAVELENGTH (μm)

28

Integrated Optical Parametric Devices

W. SOHLER, B. HAMPEL, R. REGENER, R. RICKEN, H. SUCHE, AND R. VOLK

(Invited Paper)

Abstract—A short review of the development and the state of the art of integrated optical parametric devices for nonlinear optical frequency conversion is given. The special aspects for phase matching and field overlap in waveguide devices are discussed. Material systems used for second-order nonlinear effects are reviewed. Finally, resonant Ti:$LiNbO_3$ devices for second-harmonic generation and parametric oscillation are presented and discussed in more detail.

I. Introduction

With the advent of the laser 25 years ago it became possible to operate parametric devices—well known from microwave physics for a long time—also in the optical regime. Now a nonlinear crystal is pumped by a laser beam of high intensity yielding a polarization term proportional to the square of the optical field. This leads to second harmonic generation (SHG), which was observed for the first time by Franken *et al.* in 1961 [1]. If a second optical wave of another frequency passes the crystal, polarization terms of sum and difference frequencies also occur. In case of phase matching of the polarization wave and the generated fields their amplitudes can grow up to figures comparable with those of the pump wave. This growth occurs at the expense of the pump, expressed very clearly by the language of quantum mechanics: one pump photon is annihilated if a signal and idler photon are created. This process can be spontaneous (parametric fluorescence [2]) or stimulated (parametric amplification and difference frequency generation) (see, for example [3]). It is obvious that energy and wave vector conservation (phase matching) determine the parametric processes. These effects are the bases of parametric devices which were developed mainly as tunable sources of coherent radiation in the near-infrared spectral region; the best known device is the parametric oscillator (see, for example [4]) which was invented by Giordmaine and Miller [5] in 1965.

While bulk optical parametric devices demand high-pump intensities and, therefore, high-power lasers, integrated optical versions have the potential to be operated with very low-power levels. This was recognized very soon in the early days of integrated optics (see, for example [6]). Due to the concentration of optical fields in a (long) waveguide with cross section dimensions of the order of a wavelength, a high light intensity can be maintained along the whole interaction length (which can approach the waveguide length). Diffraction effects, as in bulk optics, are avoided. Therefore, very efficient nonlinear optical interactions can be expected in guided wave structures. Furthermore, phase matching can be achieved even in isotropic materials which is not possible in bulk optics. And finally, nonlinear integrated optical devices are small, rugged, and stable in comparison with their bulk counterparts; this is especially true for integrated versions of optical resonators.

All these attractive prospects of integrated optical parametric devices stimulated many groups in the last few years to investigate nonlinear effects in integrated optical waveguides [7] and [7, references]. The aim of these efforts is to fabricate small, eventually tunable, integrated optical parametric devices for efficient frequency conversion with low power (semiconductor) lasers as a pump source. There are numerous very interesting applications for such devices in spectroscopy, optical storage, and communication systems.

It is the aim of this paper to give a short review of the development and the state of the art of integrated optical parametric devices. The special aspects, arising from the integration in optical waveguides, are discussed in the next two sections. The materials used for nonlinear optical experiments with guided waves are reviewed in Section IV. In Section V our own results obtained with resonant devices are presented.

II. Phase Matching in Waveguide Structures

Parametric processes require phase matching of the interacting optical modes to achieve a reasonable conversion efficiency. This means, e.g., for second harmonic generation: $k(\omega) + k(\omega) = k(2\omega)$, resulting in $n(\omega) = n(2\omega)$. In bulk optics only birefringent nonlinear materials allow—by coupling waves of orthogonal polarization—to fulfill this relation. In integrated optics, however, several methods exist to achieve further phase matching; they are presented in this section together with the birefringence—analog for the special case of second harmonic generation. It is obvious that these methods can be used also for other parametric processes.

A. Birefringence

In optically birefringent waveguides the fundamental mode excites a second harmonic wave of orthogonal polarization if phase matching is adjusted. This can be achieved for a collinear interaction by a wavelength, tem-

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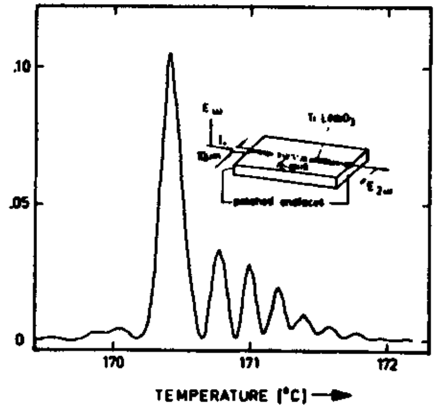

ig. 1. SHG (λ_f = 1.15 μm) in a Ti:LiNbO$_3$ channel guide [8]; phase matching by temperature tuning of the birefringence: $k_\omega^{TM_{00}} + k_\omega^{TM_{00}} = k_{2\omega}^{TE_{00}}$.

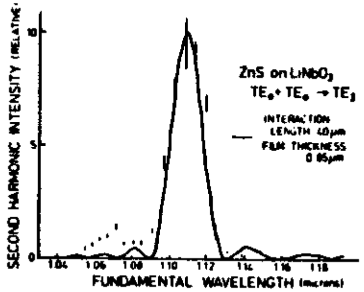

Fig. 2. SHG in a ZnS-waveguide on LiNbO$_3$ (after Ito and Inaba [12]); phase matching by modal dispersion: $k_\omega^{(0)} + k_\omega^{(0)} = k_{2\omega}^{(2)}$.

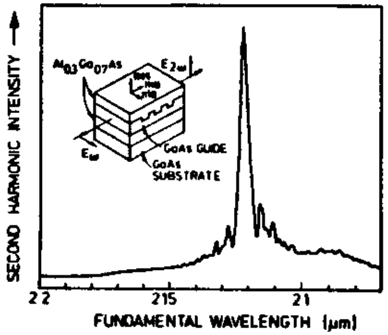

Fig. 3. SHG in a GaAs-waveguide (after van der Ziel et al. [13]); phase matching by a grating structure of periodicity Λ: $k_\omega^{(0)} + k_\omega^{(0)} + 2\pi/\Lambda = k_{2\omega}^{TM_{00}}$.

...erature, or angle tuning. The last method is applicable ...nly for planar guides. For the most desirable 90°, un...ritical interaction configuration Fig. 1 presents as ex...mple second harmonic generation in a Ti:LiNbO$_3$ opti...al waveguide with TM → TE coupling of the fun...amental modes in a y-cut crystal [8]. The second har...monic power is shown versus the waveguide temperature ...btained with approximately 30-μW fundamental power ...λ_f = 1.15 μm). The deviations of the experimental result ...rom the theoretical sinc^2-response function allow an es...imation of the inhomogeneity of phase matching in the ...aveguide structure.

... Modal Dispersion

In multimode optical waveguides a nonlinear coupling ...f modes of different order is possible. This can again be ...n interaction of modes of different polarization leading ...o a broadening of the phase-matchable wavelength range ...a corresponding example with Ti:LiNbO$_3$ guides is given ...n [9]). If the amplitude of the index profile of the optical ...aveguide is large enough the material dispersion can be ...ompensated by the modal dispersion: a coupling of a low...rder fundamental to high-order harmonic modes be...omes possible even for the same polarization. Integrated ...ptics, therefore, allows us to use even isotropic materials ...or nonlinear parametric devices. This is of great impor...ance as strongly nonlinear materials like GaAs [10] or ...he organic PCPU [11] could be used as waveguide ma...terials for second-harmonic generation. As an example—...aken from a paper from Ito and Inaba [12]—the results ...f second-harmonic generation in a ZnS-film on LiNbO$_3$ ...ia a TE$_0$ − TE$_2$ coupling are given in Fig. 2.

... Grating Structure

Another way to achieve phase matching is the coupling ...f fundamental and harmonic modes by a periodic grating structure on top of the guide or (more generally) by a periodic modulation of the (linear or nonlinear) waveguide properties [13]–[15]. This approach is especially useful if birefringence and modal dispersion fail to achieve phase matching. However, the conversion efficiency is in general drastically reduced [14]. As an example, Fig. 3 presents a phase-matched second-harmonic generation in a periodic GaAs waveguide taken from van der Ziel et al. [13].

III. Overlap of Modal Fields

Nonlinear processes with guided optical waves are effective only in that part of the waveguide where the modal fields overlap. Therefore, the efficiency of frequency conversion by integrated optical parametric devices is essentially determined by an overlap integral of the interacting fields (integration over the waveguide cross section) [7]. This normally leads to a drastic reduction of the conversion efficiency, if modes of a different order are coupled. Even for the interaction of fundamental modes in optical waveguides with a graded index profile a serious problem arises: as the size of a field distribution depends on the wavelength, an incomplete overlap is the result. This is

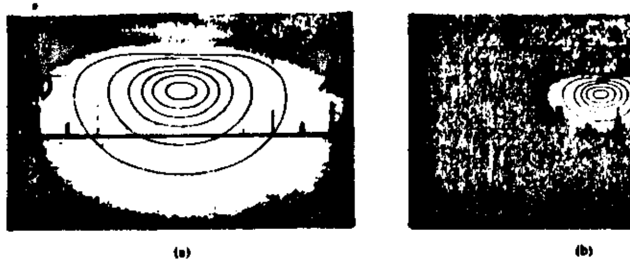

Fig. 4. Near field distributions (photographs) of (a) the fundamental TM$_{00}$ (λ_f = 1.15 μm) and (b) harmonic TE$_{00}$ modes in a 20-μm-wide Ti:LiNbO$_3$ channel guide on a y-cut substrate. Results of a finite element calculation [20] plotted as solid (90, 70, 50, 30, 10, and 1 percent) lines. Scale: 5 μm between (large) marks.

illustrated by Fig. 4 for second-harmonic generation in a Ti:LiNbO$_3$ channel guide; it demonstrates that the optimization of the overlap in such structures is of great importance. Several methods have been proposed and investigated [16], [17]; we prefer to fabricate guides of low Ti-concentration for the LiNbO$_3$ system [18]. A careful theoretical study of the influence of numerous waveguide parameters has confirmed this idea [19].

IV. Materials

In bulk optics quite a lot of very useful crystals for parametric devices are known. Most of them have been investigated in detail, so that their indices of refraction, their bandgap, their absorption coefficients, and the tensors of nonlinear coefficents can be found in the literature (see, e.g., the Table II in [21]). However, most of them have not yet been used for (nonlinear) integrated optics. It turned out that it is often very difficult to prepare epitaxial (to maintain the nonlinearity) layers on a suited substrate as an optical waveguide system. Furthermore, only low loss and very homogeneous guides can be used for nonlinear optical applications, as an interaction length of more than a centimeter is normally required.

Nevertheless, there are some material systems which could be prepared for applications in nonlinear integrated optics. Most of them were studied in experiments for second-harmonic generation. ZnS-layers on TiO$_2$ [16], ZnO [22], glass [23], and LiNbO$_3$ [12] were investigated. ZnO- [24], glass- [25], Al$_2$O$_3$- [26], and TiO$_2$- [27] waveguides, deposited on a single-crystal quartz substrate as nonlinear material, were studied. With experiments using GaP layers on CaF$_2$ [28] and GaAs guides on Ga$_x$Al$_{1-x}$As [29] it was proven that optically isotropic materials can be used for integrated nonlinear optics.

By far the best results up to now have been obtained with the Ti:LiNbO$_3$ system. There are not only very interesting devices for second-harmonic generation [30], [31], [41], but also for difference frequency generation [32], parametric amplification [33] and oscillation [34]. Recently, de Micheli et al. [35] have shown that the phase-matching range for second-harmonic generation can

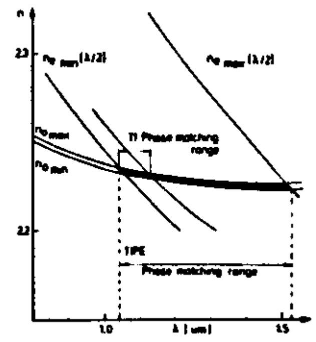

Fig. 5. Phase matching diagram for second harmonic generation with TIPE-guide; after de Micheli et al. [37].

be considerably extended with Ti diffused/proton exchanged ("TIPE"-) waveguides (see Fig. 5). Another consequence is the possible reduction of the operation temperature of an integrated optical parametric oscillator if fabricated with a TIPE-guide [36]. Unfortunately, the quality of such guides is not yet sufficient to allow the fabrication of resonant devices. On the other hand, the optical damage is considerably reduced in TIPE-waveguides [37], as well as in guides prepared by Ti-diffusion in Mg-doped LiNbO$_3$ crystals [38]. Very encouraging results—up to 800-mW second-harmonic power in cw operation—have just been reported by Fejer et al. [38]. Nevertheless, the conversion efficiency for e.g. SHG is limited to about 1 percent in 2-cm long Ti:LiNbO$_3$ guides with 20-mW fundamental power [36]. As 10 percent are necessary for many applications, other device configurations (see Section V) or better materials have to be used. Some organic crystals like MNA (2-methyl-4-nitroaniline) or PCPU (parachlorophenylurea) have very large nonlinear coefficients (∼ one order of magnitude larger than those of LiNbO$_3$) and promise, therefore, considerably better results [39]. However, up to now only few

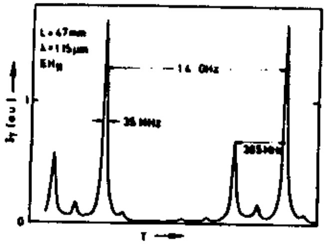

Fig. 6. Transmitted intensity I_T through an integrated optical channel waveguide resonator versus its temperature (operation as optical spectrum analyzer of the λ = 1.15 μm He-Ne-laser emission). Free spectral range (1.4 GHz) corresponds to $\Delta T = 0.29°C$.

attempts have been made to prepare optical waveguides with these materials for parametric devices [11], [40].

V. Resonant Parametric Devices

To improve the efficiency of second-harmonic generation, we have proposed to use integrated optical resonators to get an enhancement of the intensity of the fundamental wave [42]. The attainable improvement is of course strongly dependent on the resonator finesse. Resonant structures are also necessary for parametric oscillators. In this case the threshold pump power depends very critically on the quality of the resonator. For both applications we have prepared integrated optical resonators by coating the polished end faces of low-loss (<0.1 dB/cm), single-mode (TM-polarization, λ = 1.15 μm), y-cut, x-propagating Ti:$LiNbO_3$ channel guides with dielectric mirrors of reflectivity up to 99 percent. The quality of such a device is investigated by using it as an optical spectrum analyzer [43]. Fig. 6 presents as an example the measured spectrum of a He-Ne laser, emitting two longitudinal modes of 385 MHZ mode spacing at λ = 1.15 μm. The finesse of the symmetrical resonator used in this experiment was 40, defined by its free spectral range divided by the frequency resolution of 35 MHz.

A. Resonant Second-Harmonic Generator

With a 48-mm-long channel waveguide resonator of finesse 18 (reflectivity of ~0.96 at both end faces) at λ = 1.15 μm we studied second-harmonic generation. The phase-matching condition required a crystal temperature of about 176°C. Furthermore, the device had to be tuned to a resonance to generate the fundamental intensity enhancement inside the cavity. If both conditions were approximately fullfilled, second-harmonic generation could be observed (Fig. 7). The conversion efficiency was about $1 \cdot 10^{-3}$ with 1.5 mW (external) fundamental power. This result is of reasonable agreement with the theory.

However, the maximum improvement of the efficiency can be obtained with matched resonators as demonstrated in bulk optics [44]. The idea is to trap the fundamental wave in the resonator completely where it is absorbed or converted to a second-harmonic wave. A matched resonator, therefore, has a 100-percent rear mirror and a matched loss- and length-dependent front mirror to yield zero reflectivity in a resonance. In this way the fundamental field enhancement and—as a consequence—the conversion efficiency are optimized. Calculations with experimentally determined waveguide parameters show [9] that very efficient (>10 percent) harmonic generators could be fabricated in this way (assuming again 20 mW fundamental power).

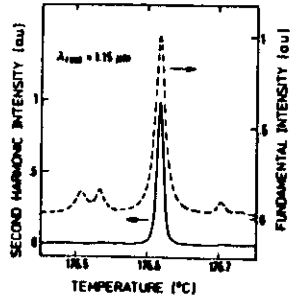

Fig. 7. Transmitted fundamental and generated second harmonic intensity in arbitrary units as function of temperature of the waveguide resonator.

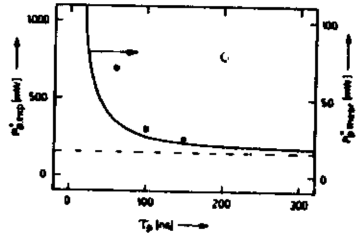

Fig. 8. Experimentally observed (dots; left scale) and calculated (solid line; right scale) pump power level P_p to achieve an infrared emission of 10 μW resp. 1 μW as function of the duration of the pump pulses. Dashed line: calculated CW pump power threshold.

B. Integrated Optical Parameter Oscillator

The symmetrical waveguide resonator of the above example (Fig. 6) was operated as optical parametric oscillator by pumping it with short pulses (up to 150 ns) from a flashlamp-pumped dye laser (λ_p ~ 600 nm; 5 pps). To achieve phase matching the device was heated to about 250°C depending on the pump wavelength and the desired output. With 60-ns-long pump pulses parametric oscillation of infrared radiation set in—defined by a signal to noise ratio of two in our detection system—at pump peak powers of about 700 mW; with 150-ns-long pulses this level was reduced further to 250 mW. These experimental results are given in Fig. 8 together with the results of calculations of the pump power level to achieve an infrared output power of 1 μW as function of the duration τ of the pump pulses. The theoretical limit for $\tau \to \infty$ is

the steady-state threshold power of 15 mW (inside the oscillator). Comparing the experimental results with the theory demonstrates that a further reduction of the threshold pump power down to about 150 mW (measured outside the oscillator) can be expected for longer pulses.

The experimentally observed tuning range coincides for doubly resonant operation (both signal and idler waves are resonant) with the mirror reflection band from 1.10 μm < λ < 1.35 μm; tuning of the crystal temperature required a shift of the pump wavelength according to theory. The singly resonant operation mode would allow to extend the tuning range of the parametric oscillator further. As an example we had demonstrated earlier a tuning range from 0.96 to 1.6 μm with a single device [9].

VI. Conclusion

Integrated optical parametric devices promise a number of advantages. Due to the high-optical power density along the whole interaction length, pump power levels orders of magnitude lower than necessary in bulk optics should be possible. Many material systems have been investigated mainly by experiments to second-harmonic generation. However, only the Ti:$LiNbO_3$ system has proven to answer most of the expectations set in nonlinear integrated optics. The most promising devices are resonant Ti:$LibO_3$ structures for second-harmonic generation and parametric oscillation. A conversion efficiency of harmonic generation up to 10 percent with 20-mW fundamental power seems to be feasible; therefore, a semiconductor laser might be used as pump source. The parametric oscillator can be operated with 250-mW pump power; its tuning range is 1.1 μm < λ < 1.35 μm. A further reduction of the threshold and an extension of the tuning range are possible allowing infrared spectroscopy from laser monitoring of the atmosphere (molecular spectroscopy) to investigations of optical waveguides and waveguide devices.

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