UCRL-JC-123111 Rev 1
PREPRINT

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This paper was prepared for submittal to the
Society of Photo-Optical Instrumentation Engineers Conference
Denver, CO
August 4-9, 1996

September 1996

Lawrence Livermore National Laboratory

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Abstract

We describe a first generation mid-infrared transmitter with pulse-to-pulse frequency agility and both wide and narrowband capability. This transmitter was used to make multicomponent DIAL measurements in the field.

I. Introduction

The simultaneous extraction of accurate concentrations of multiple species, or the concentration of a single species in the presence of a complex, fluctuating background, requires the extension of traditional two-line DIAL techniques to multiple wavelengths[1]. For example, to obtain separate concentration estimates of m chemicals with highly overlapped absorption spectra, a minimum of m+1 different wavelengths is required. For optimum sensitivity, these wavelengths must be placed at or near particular values over the relevant spectral region. In addition, for long range DIAL measurements, the lines must be centered on atmospheric transmission bands. Thus, a flexible multiwavelength DIAL transmitter must be able to generate an arbitrary selection of wavelengths within some relevant spectral region.

The time format of the multiple wavelength output is also an important consideration. It is generally appreciated that the accuracy of slow scanning modes of data collection, where, for example, the DIAL returns for N successive shots are averaged at one wavelength before scanning to the next, can be compromised by atmospheric and system baseline drifts. Moreover, for topographic backscatter DIAL, the rate at which *single* color returns can be effectively averaged is limited by the speckle decorrelation time, which is generally longer than a millisecond even for data acquired at aircraft velocities[2]. In this situation, the DIAL data acquisition rate can only be increased by interleaving the m+1 single color data streams. Therefore the mode of operation for multiple wavelength DIAL which obtains the most accurate concentration estimates in the shortest time is one in which each wavelength is emitted successively, and the pattern of wavelengths is repeated at the maximum repetition rate consistent with the decorrelation time for a single wavelength. This "wavelength agile" operational mode is illustrated in figure 1.

Until recently, the only transmitters capable of pulse-to-pulse wavelength agility over a wide frequency band were based on the grating tuned CO_2 laser, and thus were restricted to operation on the discrete sets of isotopic CO_2 laser lines[3]. In this paper we report on the development of frequency agile, *all solid state* laser transmitters which have pulse-to-pulse frequency agility at kilohertz repetition rates, with continuous or near-continuous access to arbitrary frequencies within a wide spectral range. Three advances in fundamental laser technology underpin the development of these transmitters. First, kilohertz repetition rate, high beam quality Nd:YAG oscillators/amplifiers have been enabled by the development of high power diode pump sources and parametric 4-wave SBS phase conjugation. Second, we have developed rapidly tunable optical parametric oscillators (OPOs) which are based on noncollinear phasematching and acousto-optic pump angle deflection. Finally, we have constructed flexible multiwavelength seed sources which use volume phase holograms and spatial light modulators to disperse and spectrally filter the output of low power, mode-locked laser oscillators.

These technologies have been implemented in a first-generation mid-infrared frequency agile LIDAR transmitter which we have recently field tested. This transmitter permits multiwavelength DIAL over a $\approx$200 cm^{-1}

region centered around 3.4 μm, allowing the deconvolution of mixtures of broadband absorbers such as typical hydrocarbons. In addition, narrow absorption features and their backgrounds can be mapped out with sub-GHz resolution within a ≈2 cm^{-1} window. The system is designed to operate at repetition rates up to 1 kHz, and was used to generate real time concentration estimates of the components of mixtures of up to 4 gases with highly overlapped spectral features in an artificial plume at a standoff range of 7.3 km.

In the following section we describe the overall transmitter architecture. In sections 3, 4 and 5, the high beam quality pump, rapidly tunable OPO, and multiwave seeder subsystems are discussed in more detail. A brief summary of the results of field testing is given in section 6.

2. System overview

Figure 2 shows the overall system architecture utilized in the first generation transmitter. A multiwavelength seeder (MWS) operating in the 1.06 μm region injection seeds a Nd:YAG master oscillator. The frequency of the MWS can be selected from pulse to pulse from a set of lines separated by ≈600 MHz and covering a range of more than 60 GHz. The output of the oscillator is amplified and used to pump one of two parametric oscillators. One OPO is rapidly tunable over ≈200 cm^{-1} in the 3-4 μm region. This device uses an acousto-optic deflector to change the pump beam angle, which provides the tuning mechanism. The other OPO is a standard angle tuned device which is injection seeded with a commercial external cavity tunable diode laser[4]. The seeded OPO has an output bandwidth of ≈300 MHz and its output is tuned over a 60 GHz range by changing the pump frequency by means of the MWS. The rapidly tunable OPO bandwidth is controlled by a low finesse etalon, and is typically a few tenths of a wavenumber. A Pockels cell/polarizer combination allows pulse to pulse switching between the two OPOs, whose output beams are polarization combined into a common path. A common timing/control bus sends the appropriate bits to the MWS, the Pockels cell and the deflector to output the desired wavelength on each pulse. In a given experiment a finite set of wavelengths which optimize the DIAL measurement are chosen, and this set is cycled repetitively. Thus, independent samples of the effluent spectrum are collected at a rate given by the laser repetition rate divided by the number of wavelengths in the set.

In this first generation transmitter the broadband and seeded narrowband capabilities reside in two separate OPO modules, and the output spectral format is thus necessarily restricted. In any pulse sequence, the narrowband (seeded) emission is restricted to lie within ±30 GHz of the center wavelength for which the seeded OPO is set. Furthermore, the output of the rapidly tunable OPO is restricted to lie on a comb whose spacing is determined by the free spectral range of the etalon. Nonetheless, the output is sufficiently flexible to allow the accurate deconvolution of a wide variety of mixtures of broad- and narrowband absorbers as will be discussed in section 6. Moreover, methods of incorporating injection seeding into the rapidly tunable OPO architecture, which results in a system with complete spectral flexibility, will be briefly described in section 4.

3. High repetition rate, high beam quality Nd: YAG pump source

The pump laser for the OPO consists of a diode pumped Nd:YAG master oscillator and power amplifier. The oscillator design is shown in figure 3. The ring cavity contains two separate Nd:YAG crystals which are end-pumped by fiber coupled diode laser bars. A KD*P Q-switch is operated in half-wave mode to polarization couple light out of the cavity. Injection seeding signals derived from a commercial MISER single frequency laser or from the MWS (see below) are coupled into the oscillator via single mode optical fibers. The ring cavity is locked to the seeder wavelength by a standard commercial feedback circuit which minimizes the build-up time for the Q-switched pulse. This oscillator generates up to 3 mJ/pulse with a TEM_{00} spatial profile, at a repetition rate of 1 KHz.

Light from the oscillator feeds the power amplifier shown schematically in figure 4. Two separate Nd:YAG rods are transversely pumped by a set of microchannel cooled diode laser bars[5]. A quartz rotator placed between the amplifier heads provides polarization reversal to compensate for thermally induced stress depolarization. Image relay optics ensure that the irradiance profiles of the beam are free of diffraction structure as they pass through the amplifier rods. Of crucial importance is the multipass phase conjugator cell which effectively acts as a wavefront reversing "mirror" allowing aberrations acquired by the beam during the first pass through the amplifier rods to be corrected on a second pass. The multipass phase conjugation architecture permits high effective reflectance with modest pulse energies. Even $\approx$2 mJ pulses from the master oscillator alone see significant reflectivity, allowing us to use the unamplified beam for optical alignment downstream of the amplifier.

The amplifier provides pulse energies up to 40 mJ with inputs of $\approx$2mJ from the master oscillator, at repetition rates up to 1 kHz. The beam quality has been determined by beam profiling and energy-in-the-bucket measurements to be much better than 2 times diffraction limited.

4. Rapidly tunable OPO

The rapidly tunable OPO is based on the concept shown in figure 5. A fast beam deflector changes the angle of the pump beam within a parametric oscillator whose crystal and resonator are fixed in space. A telescope forms an image relay from an object plane at the pivot point of the beam deflector to an image plane at the OPO midplane, thus ensuring (to lowest order) that the pump irradiance profile does not change position in the OPO as the pump angle is changed. Since the resonator axis exerts a strong anchoring effect on the direction of the resonated wave (the "signal" wave), phasematched regenerative parametric amplification occurs in a noncollinear mode with the idler wave angle adjusting itself adiabatically as the pump angle changes. Figure 6 shows an empirically determined tuning curve (output wavelength vs. pump deflection angle) for a lithium niobate OPO resonating in the 1.55 μm range.

Because tilting the pump beam changes the spatial overlap of the gain volume with the mode volume of the OPO cavity one might also expect reduced conversion efficiency, distortions in the transverse spatial profile, and changes in the spectral lineshape of the output beams as the pump angle is changed. We have observed all of these effects in practice, but they are typically small over the angle changes required to obtain a useful tuning range. Figure 6 displays the observed change in output energy of the OPO as it is tuned across ≈500 cm^{-1}.

There are two practical methods of fast pump beam deflection. Acousto-optic (A.O.) beam deflectors can provide several tens of milliradians of deflection with random access times of ≈10 μs, thus providing a basis for deflection (tuning) rates of greater than 10 kHz. An A.O. beam deflector also provides a method of correcting the angular deviations of the OPO output, if necessary. Galvanometric mirror deflectors can be used to obtain even larger angular changes at random access rates approaching 1 kHz. In addition, the efficiency of these devices is just the mirror reflectivity, and can easily exceed 99%. Clearly, a galvanometric mirror and acousto-optic deflector can be combined, with the mirror providing "coarse" angle changes at a reduced duty factor and the acousto-optic modulator providing "fine" angle tuning at the full repetition rate.

Several line narrowing methods can be envisioned in conjunction with the rapid tuning scheme described here. Injection seeding of the resonated wave requires that the seed laser output be matched to OPO cavity modes. There are two basic architectures which can fulfill this requirement. In one architecture, a finite number of discrete diode lasers are multiplexed and injected simultaneously into the OPO cavity. The OPO cavity length is locked to resonance with one "master" seed laser, and the remaining seed lasers are then locked to resonances of the OPO cavity. The "master" seed laser wavelength could be set, for example, to hit a particular narrowband absorption line, while others could be set near the centers of particular atmospheric transmission bands. A more general architecture would result from constructing a frequency agile multiwave seed (MWS) source (see below) which covers the entire tuning range accessed by the resonated wave in the OPO. The fundamental mode spacing of the multiwave seeder must match the OPO longitudinal mode spacing (typically in the ≈1GHz range) or some multiple or submultiple of it. The desired seed wavelength would then be switched out of the MWS and injected into the OPO in synchrony with the pump angle deflection.

Passive line narrowing techniques are also compatible with the rapid tuning scheme outlined above. A fixed etalon allows rapid tuning over a set of narrowed lines whose spacing is related to the free spectral range of the etalon, and whose spectral width is determined by the etalon finesse. To make the tuning behavior truly continuous, it would be necessary to scan the etalon (perhaps electro-optically) to place the pass-band in the center of the OPO gain bandwidth as the pump angle is changed.

The rapidly tunable OPO which was implemented in the first generation transmitter consisted of a 5 cm-long lithium niobate crystal, and cavity optics which were coated to resonate in the 3-4 μm region. A commercial A.O. modulator and a galvanometric mirror were used in combination to deflect the pump beam. A 3.5 cm^{-1} FSR, uncoated zinc selenide etalon was used for line narrowing. The output pulse energies were 50 - 100 μJ and frequency sets containing as many as 20 lines (but more typically 8 - 10) covering more than 120 cm^{-1} were generated for DIAL measurements in the field.

5. Multiwavelength seeder

In previous work, we demonstrated 3 line DIAL using three separate narrowline lasers to injection seed a Nd:YAG pump source which was used to pump a seeded OPO[4]. This year we implemented a more general N-line capability based on the architecture shown in figure 7. Pulses from a mode-locked $Nd:VO_4$ oscillator are spectrally dispersed using custom holographic volume phase grating structures, then spatially filtered by an addressable spatial light modulator. The present modulator has 256 independently addressable pixels. The resolution of the system allows the selection of any single longitudinal mode out of the several hundred modes contributing to the mode-locked pulse. The filtered light is reconstituted with a second holographic grating and directed through a single mode fiber to the master oscillator. Commercial wavelength locker technology is used to stabilize the central frequency of the mode locked oscillator. The cavity length of the master oscillator must be carefully matched to that of the mode-locked oscillator to maintain spectral fidelity.

The present system operates with an intermode spacing of 668 MHz and is capable of generating sequences of up to 150 modes selectable from the >100 GHz bandwidth of the mode locked oscillator. Because the gain bandwidth of the Nd:YAG master oscillator and amplifier is restricted to ≈60 GHz, only lines within this range are typically generated. Figure 8 shows 8 lines with 0.668 GHz spacing generated sequentially at 1 kHz, as displayed on a 10 GHz FSR etalon. In the seeded OPO, the idler wave in the 3 - 4 μm region is tuned by changes in the pump frequency. Thus, the OPO output for the pump spectrum displayed in figure 8 also consists of 8 lines with the same frequency spacing.

6. Multiwavelength DIAL measurements

The transmitter components were integrated with a high performance transceiver system, data collection and data analysis computers to produce real time multiwavelength DIAL measurements. Experiments on plumes containing mixtures of up to 4 chemicals were performed from a standoff distance of 7.3 km. Sets of 8 - 20 wavelengths, chosen to be coincident with atmospheric transmission windows and covering between 100 and 150 cm^{-1} were generated at a repetition rate of 500 Hz. Figure 9 displays a key test of our ability to deconvolve mixtures of chemicals with highly overlapping spectra using the frequency agile transmitter. Here, the presence of a single component "A" is distinguished from a possible mixture of "A", "B" and "C", all of which possess continuous and nearly featureless absorption spectra in the 2800 - 3000 cm^{-1} region. Figure 10 shows the results of several experiments comparing released and measured concentrations of both broadband and narrowband absorbers.

7. Concluding remarks

We are currently planning several extensions of the technologies described in this paper. The rapidly tunable OPO concept can be extended to longer or shorter wavelengths with appropriate changes of nonlinear crystals and/or pump wavelengths. Simplification of the overall architecture could be achieved by extending the MWS technology into the 1.5 μm region as described in section 5, thus giving the rapidly tunable OPO seeded narrowband capability. In addition, extending MWS technology into the 0.7 - 0.9 μm region could enable the development of rapidly tunable solid state transmitters based on alexandrite, LiSAF or Ti:sapphire. Finally, the extension of pump laser technology to higher repetition rates will enable the optimization of transmitters for airborne remote sensing applications.

8. Acknowledgments

The authors wish to acknowledge the contributions of a large number of colleagues who were involved in the actual construction and operation of the transmitter components. In addition, the results of the field experiments represent significant efforts in the design and construction of the transceiver, data acquisition and data analysis subsystems. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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Figure Captions

Fig. 1. Preferred mode of operation of a multiwavelength DIAL transmitter. A set of N wavelengths are cycled with a period equal to the speckle decorrelation time for a single wavelength.

Fig. 2. Architecture of the first generation frequency agile multiwavelength transmitter.

Fig. 3. Master oscillator design.

Fig. 4. Phase conjugated double pass Nd:YAG amplifier.

Fig. 5. Rapidly tunable OPO concept.

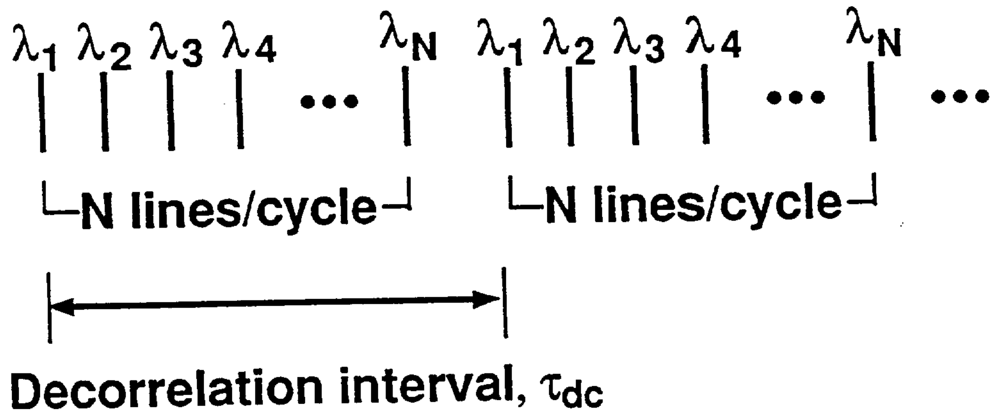
Fig. 6. OPO tuning curve and output energy.

Fig. 7. Multiwavelength seeder concept.

Fig. 8. Spectral output of the MWS, showing 16 lines displayed on a 10 GHz FSR etalon.

Fig. 9. Broadband absorber "A" can be distinguished from similar compounds "B" and "C" by the multiwavelength DIAL system. The concentration profile vs. time is representative of the release method. A sequence of two identical releases is shown.

Fig. 10. Results of DIAL measurements on several "blind" mixtures. The release concentrations in the plume were determined by mass flow measurements. Plume thickness $\approx$1 m.



λ1 λ2 λ3 λ4 ••• λN λ1 λ2 λ3 λ4 ••• λN •••
N lines/cycle
N lines/cycle
Decorrelation interval, τdc

Fig. 1

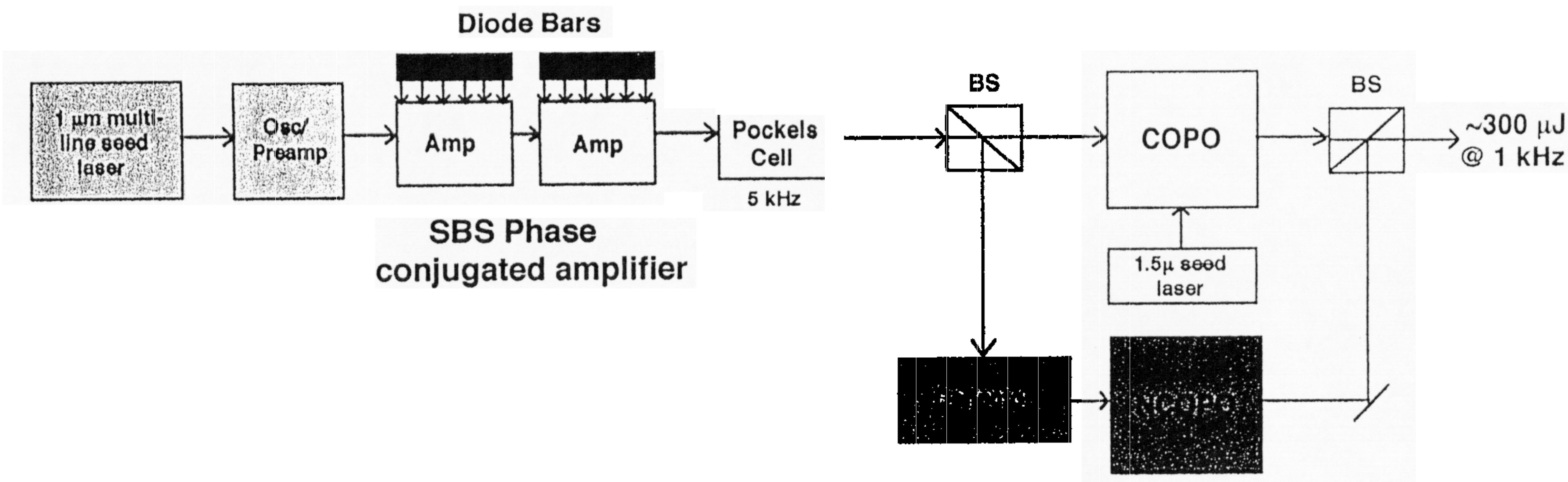

Diode Bars
1 µm multi-line seed laser
Osc/ Preamp
Amp
Amp
Pockels Cell
5 kHz
SBS Phase conjugated amplifier
BS
COPO
BS
~300 µJ @ 1 kHz
1.5µ seed laser

Fig. 2

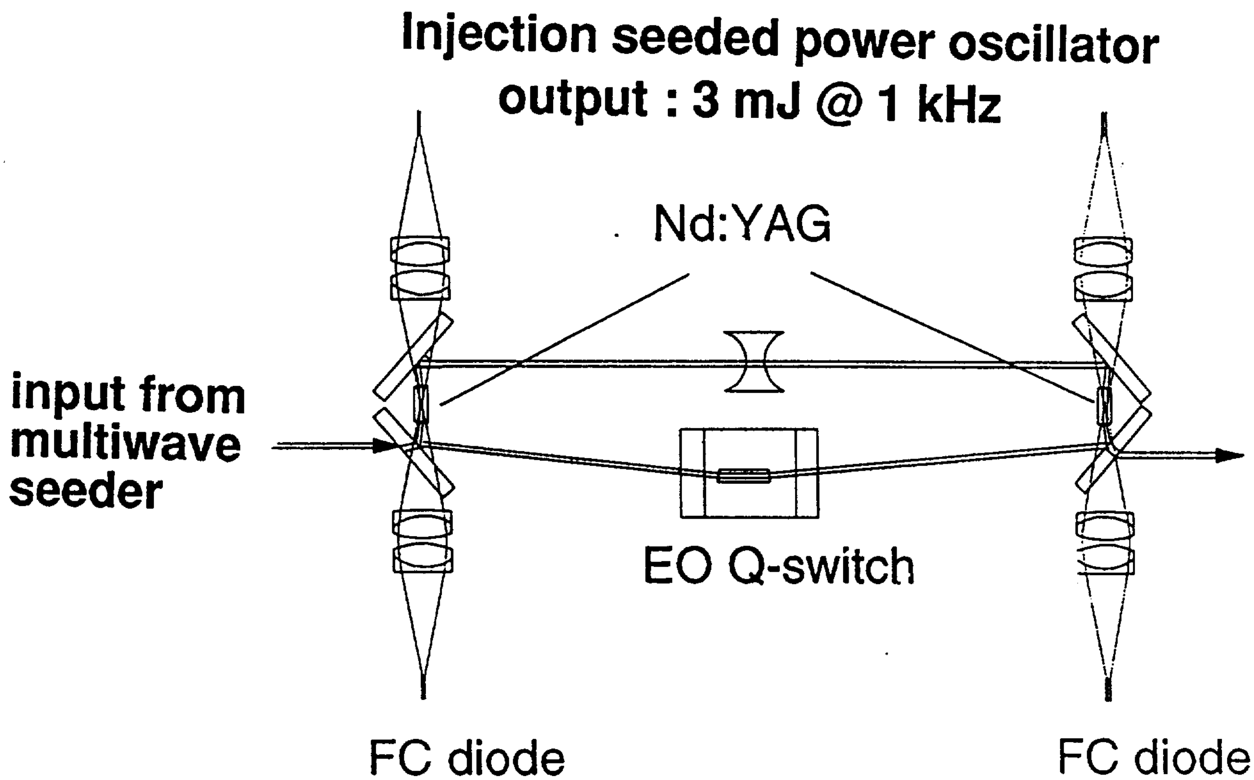

Injection seeded power oscillator
output : 3 mJ @ 1 kHz
Nd:YAG
input from
multiwave
seeder
EO Q-switch
FC diode
FC diode

Fig. 3

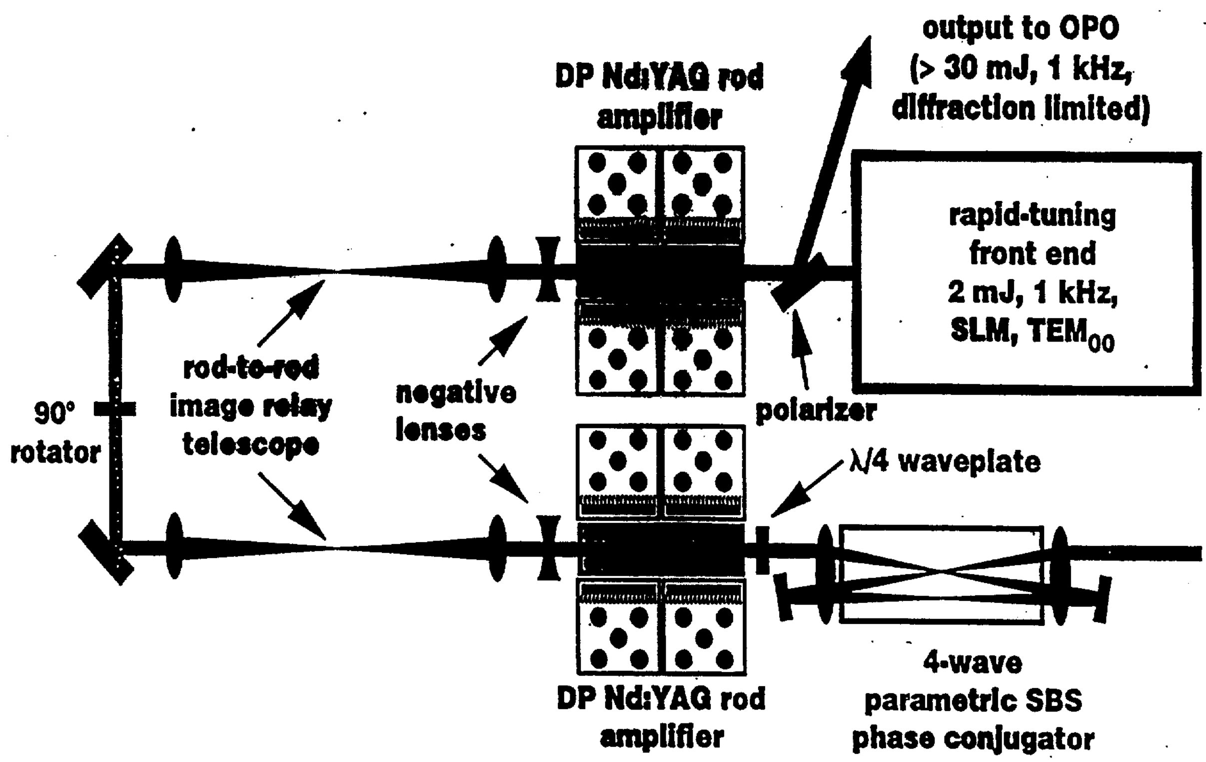

output to OPO
(> 30 mJ, 1 kHz,
diffraction limited)
DP Nd:YAG rod
amplifier
rapid-tuning
front end
2 mJ, 1 kHz,
SLM, TEM00
90°
rotator
rod-to-rod
image relay
telescope
negative
lenses
polarizer
λ/4 waveplate
DP Nd:YAG rod
amplifier
4-wave
parametric SBS
phase conjugator

Fig. 4

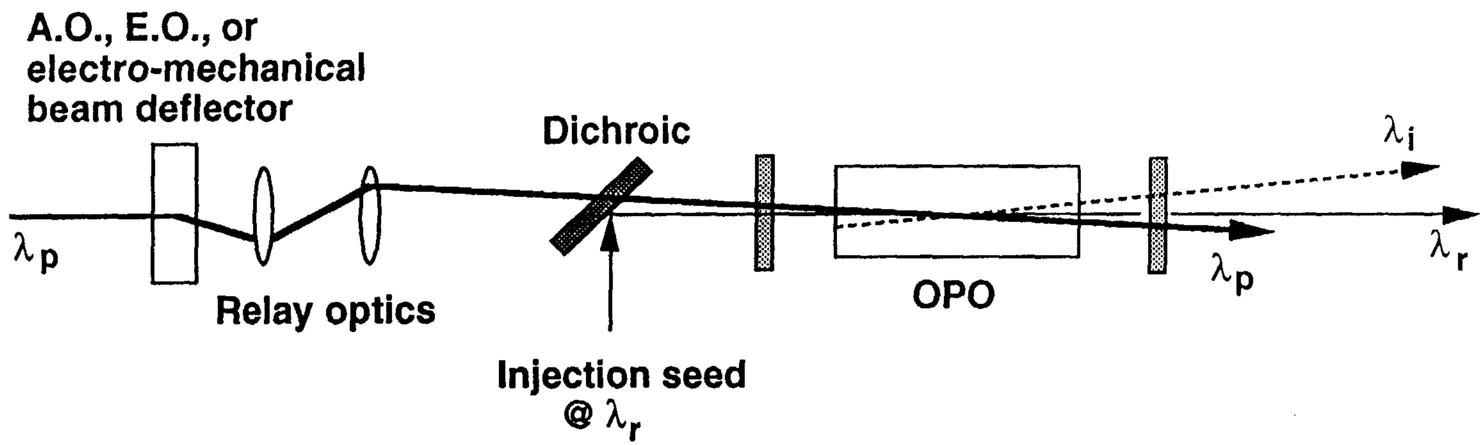

A.O., E.O., or
electro-mechanical
beam deflector
λ_p
Relay optics
Dichroic
Injection seed
@ λ_r
OPO
λ_i
λ_r
λ_p

Fig. 5

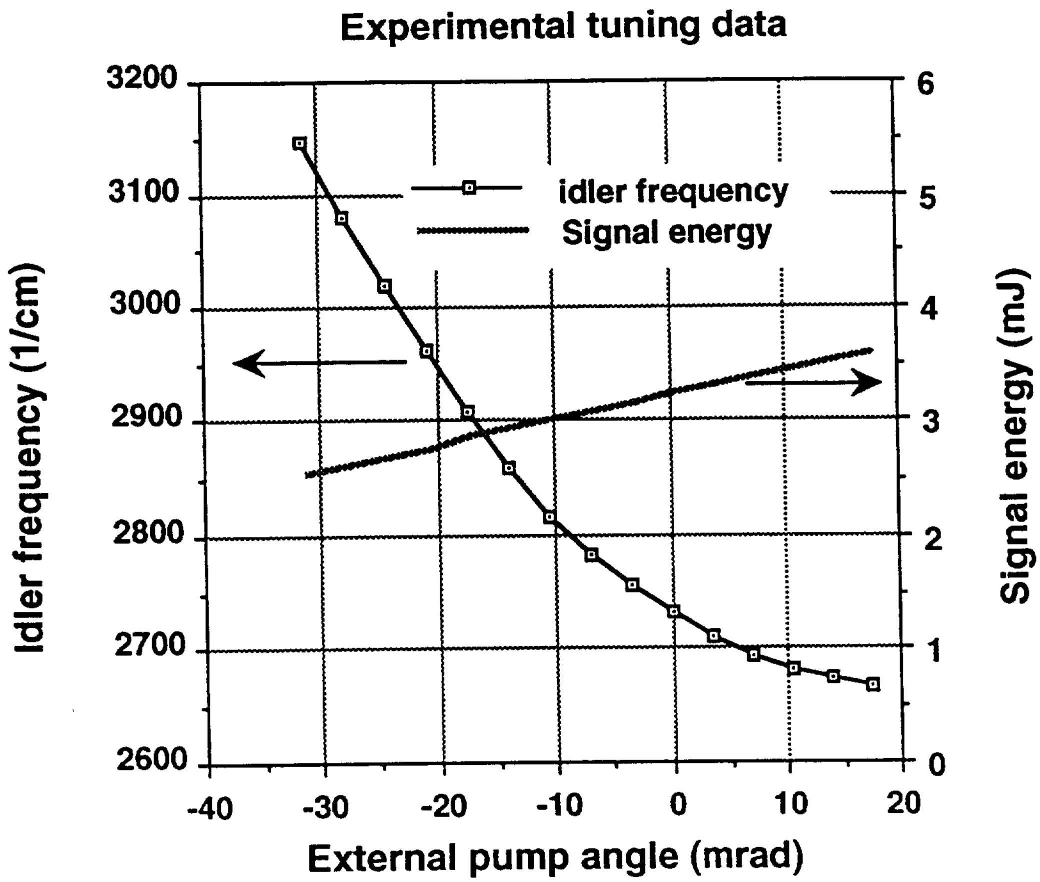

Experimental tuning data
idler frequency
Signal energy
Idler frequency (1/cm)
Signal energy (mJ)
External pump angle (mrad)
3200
3100
3000
2900
2800
2700
2600
6
5
4
3
2
1
0
-40
-30
-20
-10
0
10
20

Fig. 6

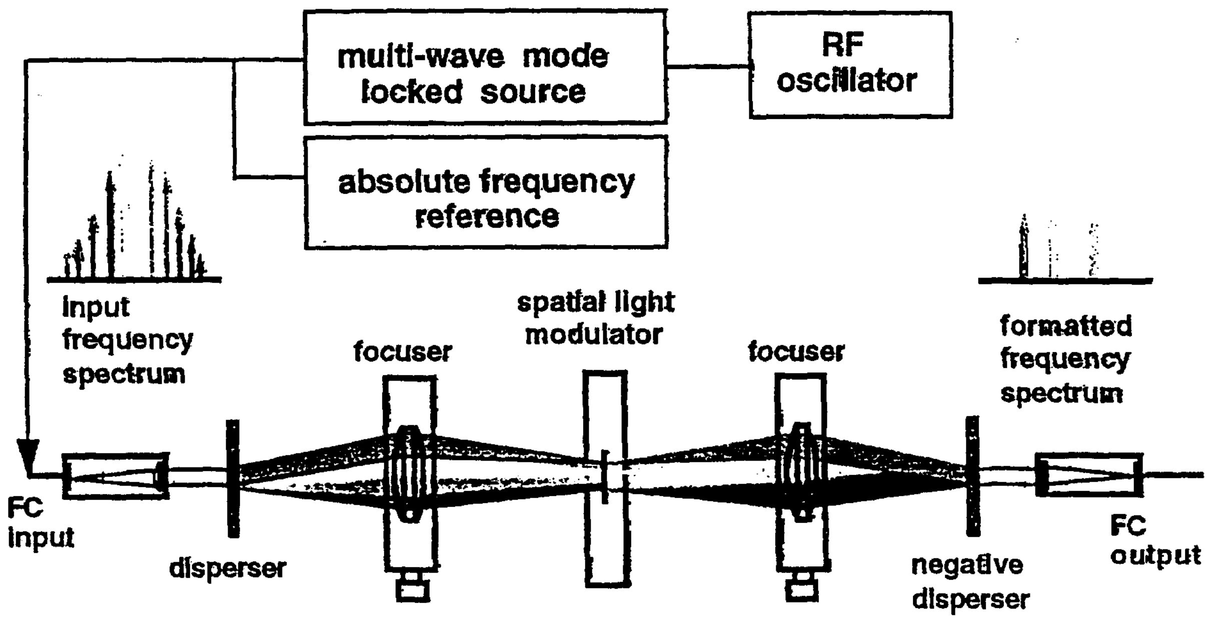

multi-wave mode locked source
RF oscillator
absolute frequency reference
input frequency spectrum
spatial light modulator
focuser
focuser
formatted frequency spectrum
FC input
disperser
negative disperser
FC output

Fig. 7

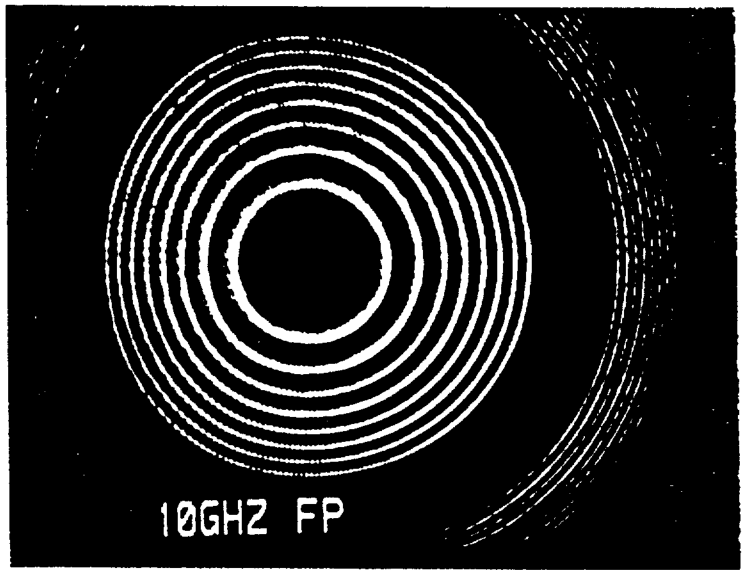


Fig. 8

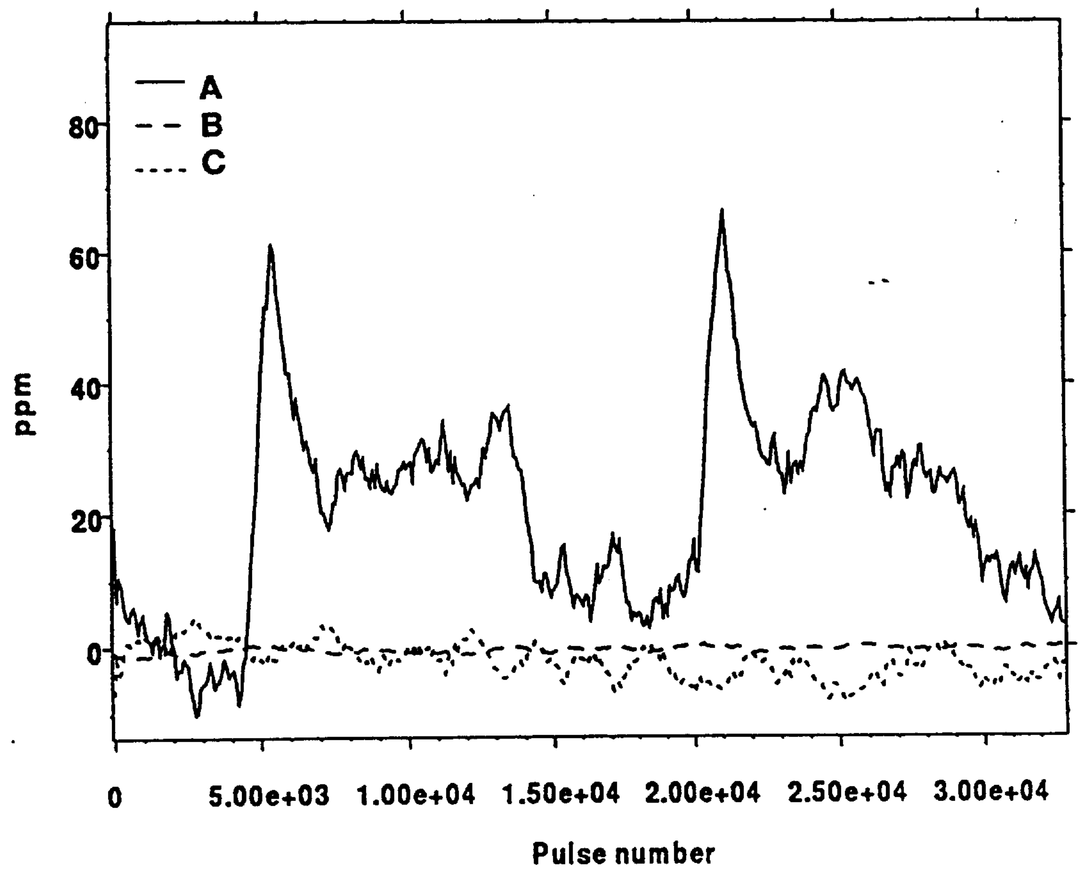
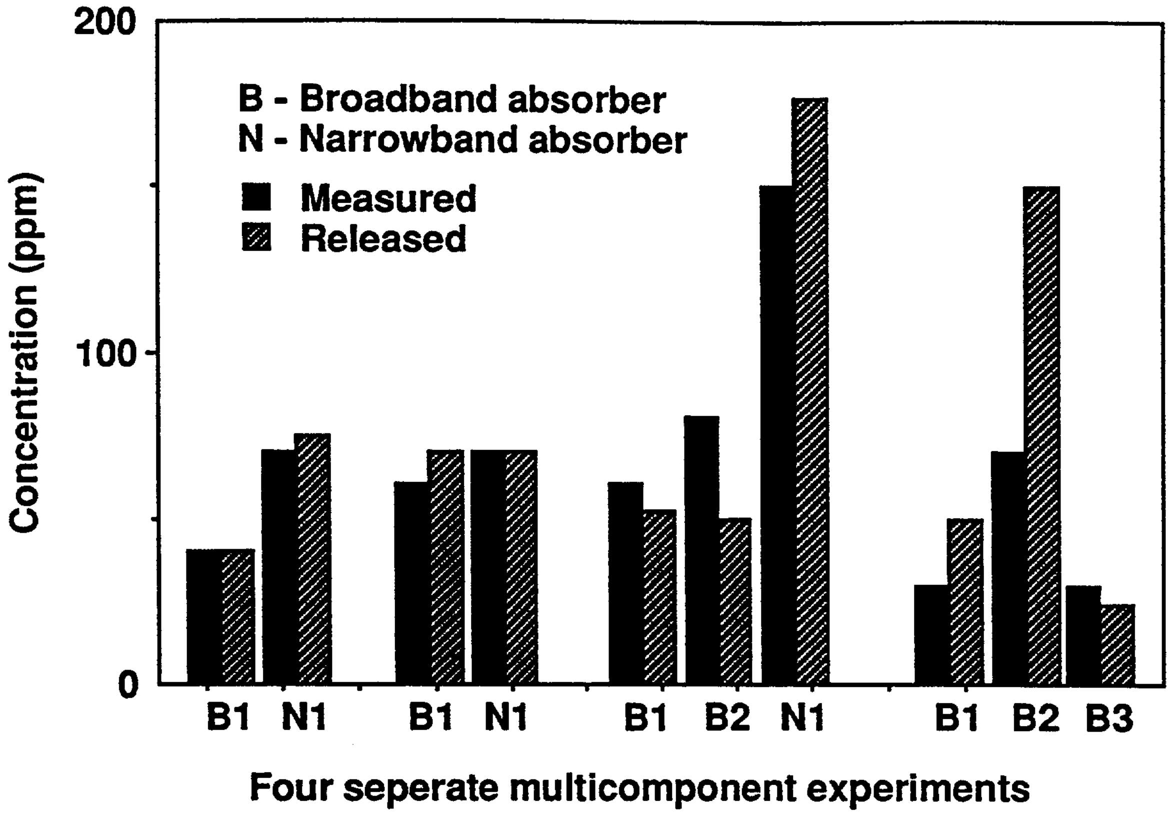

A
B
C
80
60
40
20
0
ppm
0
5.00e+03
1.00e+04
1.50e+04
2.00e+04
2.50e+04
3.00e+04
Pulse number

Fig. 9



200
100
0
Concentration (ppm)
B - Broadband absorber
N - Narrowband absorber
Measured
Released
B1 N1
B1 N1
B1 B2 N1
B1 B2 B3
Four seperate multicomponent experiments

Fig. 10

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