INTERFEROMETRIC STABILIZATION OF AN OPTICAL PARAMETRIC OSCILLATOR*

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Single longitudinal mode operation of an optical parametric oscillator has been achieved using a low loss, mode-matched interferometer as a mode selector. Bandwidths of 0.001 cm^{-1} in the region of 2.5 μm have been obtained.

We have used a novel type of optical interferometer as a mode selector in an optical parametric oscillator. The interferometer is mode matched to the oscillator cavity and does not introduce either diffraction loss or the walk-off loss associated with a tilted plane-parallel etalon. The system operates consistently in a single mode with a bandwidth of 0.001 cm^{-1} in the region of 2.5 μm.

The gain bandwidth of an optical parametric oscillator is primarily determined by the phase-matching condition of the non-linear interaction [1]. For lithium niobate operated away from degeneracy the gain bandwidth is typically about 6 cm^{-1} divided by the crystal length in centimeters. Kreuzer [2] has shown theoretically that for steady state operation of a single resonant parametric oscillator gain saturation will prevent more than one mode from oscillating provided the pump power is less than 4.6 times threshold. However, a system pumped with a *Q*-switched laser pulse does not operate in steady state and is generally pumped at levels many times above threshold. Consequently, a large number of modes are observed occupying an appreciable fraction of the gain bandwidth.

The use of an internal Fabry-Pérot etalon to limit a parametric oscillator to a single mode was first demonstrated by Kreuzer [3] and has been developed recently by Wallace [4]. In principle, restricting the resonated parametric signal to a single longitudinal cavity mode does not reduce the efficiency of the oscillator, provided the element used is lossless. In addition, the full power of a relatively wide-band pump is still effective in pumping a single frequency, singly resonant parametric oscillator [5]. In practice, however, you must tilt an internal mode selecting etalon off-axis to avoid creating an extremely sensitive multiple mirror cavity. This misalignment produces a loss proportional to the mirror reflectivity, and inversely proportional to the beam size [6]. For the tightly focused beams used in non-linear interactions this loss can become quite large unless the finesse is kept low. We report here a selection scheme which eliminates this restriction.

Our system, shown schematically in fig. 1, consists of a lithium niobate crystal in an oven and three mirrors, one of which is on the back of a Littrow prism. The mirrors, M_2 and M_3, and the beam splitter S form a frequency selecting interferometer. The properties of this type of interferometer have been demonstrated by

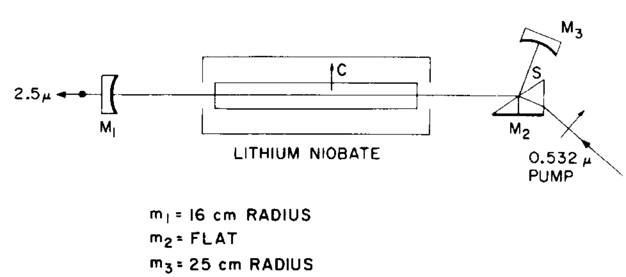

Fig. 1. Schematic of the stabilized oscillator.

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Damaschini [7]; it can be considered as the dual of the interferometer demonstrated by Smith [8]. The interferometer shown has essentially the same characteristics in reflection from the beam splitter as a Fabry-Pérot etalon has in transmission. At frequencies on resonance it exhibits a peak reflectivity

$$R_{max} = R_m R^2/(1 - TR_m)^2 ,$$

where R_m is the reflectivity of M_2 and M_3, and R is the reflectivity, and T is the transmission of the beam splitter. Off resonance the reflectivity falls to a minimum value of

$$R_{min} = R_{max}/\{1 + (2F/\pi)^2\} ,$$

where F is the finesse of the etalon and is given by

$$F = \pi(R_m T)^{1/2}/(1 - R_m T) .$$

The two cavities M_2M_3 and M_1M_3 may be perfectly mode matched without loss of frequency selectivity because there is no way in which either of the interferometer reflectors can form a low loss cavity with M_1 without selective interference taking place. Furthermore, the interferometer does not have to be tilted off-axis as the mirrors are effectively decoupled from M_1 by the low reflectivity beamsplitter. Thus no diffraction or geometrical loss is introduced into the oscillator regardless of the finesse or peak reflectivity.

The oscillator is pumped with a repetitively-pulsed and Q-switched Nd: YAG laser internally doubled to provide 5 kW peak, 125 nsec long pulses at 0.532 μm. The Brewster angle surface of the Littrow prism is oriented in a plane orthogonal to the polarization of the resonant signal forming a beam splitter having about 12% reflection. For this orientation the pump passes through the two prism surfaces very nearly at Brewster's incidence and thus suffers almost no loss. The 5 cm long lithium niobate crystal is held in a temperature controlled oven with water cooled baffle plates to shield cavity components from the heat. The mirrors are multiple layers of Si-SiO_2 having high reflectivity in the region of 2 μm to 3.5 μm. Reflectors M_2 and M_3 have a spacing of 1 cm corresponding to a confocal parameter of 10 cm and a free spectral range of 0.4 cm^{-1}. The interferometer elements are mounted in an invar block for thermal stability Reflectors M_1 and M_3 are separated by 12.7 cm to produce a confocal parameter of 10 cm and longitudinal mode spacing of 0.023 cm^{-1}. Both M_1 and M_3 are mounted on piezoelectric ceramic stacks for translation. The pump beam is also focused to a 10 cm confocal spot size. The entire oscillator is enclosed in a styrofoam box to reduce the effects of room temperature changes and air currents.

The interferometer was designed assuming a mirror reflectivity of 99% and a beam splitter of 12% which yields a theoretical peak reflectivity of 85% and a finesse of 20. We were unable to obtain oscillation under these conditions, probably because the true mirror reflectivity is lower than estimated. The peak reflectance was increased by increasing the beam splitter reflectivity to 30% with a single layer ZnS coating. (Naturally a better way to obtain the increased reflectivity would be to use an uncoated prism of suitable apex angle.) We were then able to obtain reliable operation with a threshold pump power of 2 kW. This is equal to the threshold observed when the interferometer is replaced by a flat mirror such that the beam waist size and position inside the resonator remains unchanged. We estimate the finesse of the interferometer with the coated beamsplitter to be about 10.

We analyze the output of the parametric oscillator with a very stable, confocal Fabry-Pérot scanning interferometer with a 10 cm spacing. The interferometer is used off-axis so that the effective path length is 40 cm providing a free spectral range of 0.025 cm^{-1}. Fig. 2 shows a scan of the analyzing interferometer taken over a period of about 2 minutes and representing an average of over 500 pulses. It is apparent that the oscillator runs in a single longitudinal mode. Two modes will oscillate simultaneously, however, if the peak reflectance frequency of the selecting interferometer is sufficiently detuned from exact correspondence to a cavity mode. We have found experimentally that detunings of about 0.015 cm^{-1} are possible before a second mode appears. For large changes

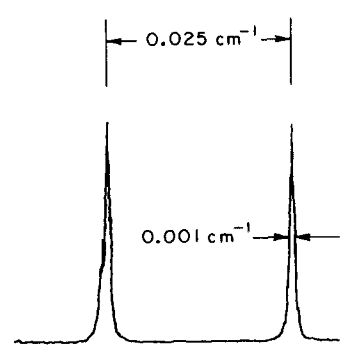

Fig. 2. Scanning Fabry-Pérot analysis of the oscillator output at 2.5 μm.

in the operating wavelength the etalon must be readjusted to compensate for the dispersion of the quartz prism. This is easily done by rotating the etalon as a unit about the center of curvature of M_3, as imaged by the beam splitter. Ultimately the tuning range is limited by the dielectric mirrors.

The bandwidth observed depends on the laboratory conditions, and appears to be due to mechanical vibrations of the cavity length. Linewidths both narrower and broader than the 0.001 cm^{-1} shown are observed regularly. We also observe a slow thermal frequency drift of typically 0.001 cm^{-1}/minute. Our optical cavity is neither exceptionally rigid nor thermally compensated. With careful mechanical design we believe an absolute frequency stability of at least 0.001 cm^{-1} without feedback loops is feasible.

An additional test of the frequency stability was made by observing the transmission of the oscillator output through a 30 cm HF absorption cell. An individual HF vibration-rotation line of the 0-1, 2.5 μm series was selected by tuning the lithium niobate thermally. Then the 0.01 cm^{-1} Doppler broadened line could be resolved easily by piezoelectrically scanning the oscillator mirror.

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