AIP | Applied Physics Letters

FREQUENCY CONTROL OF A PULSED OPTICAL PARAMETRIC OSCILLATOR BY RADIATION INJECTION

J. E. Bjorkholm and H. G. Danielmeyer

Citation: Applied Physics Letters **15**, 171 (1969); doi: 10.1063/1.1652954
View online: http://dx.doi.org/10.1063/1.1652954
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/15/6?ver=pdfcov
Published by the AIP Publishing

FREQUENCY CONTROL OF A PULSED OPTICAL PARAMETRIC OSCILLATOR BY RADIATION INJECTION

J. E. Bjorkholm and *H. G. Danielmeyer*
Bell Telephone Laboratories, Inc.
Holmdel, New Jersey 07733
(Received 16 June 1969; in final form 11 July 1969)

We have demonstrated a method of accurately controlling the spectral properties of a pulsed, singly resonant optical parametric oscillator. The resonated output of a ruby-laser-pumped $LiNbO_3$ oscillator was "locked" to the frequency of radiation injected into a mode of the oscillator cavity by a single-frequency cw Nd:YAG laser. Locking could be obtained if the peak of the oscillator gain curve was tuned to within 18 Å of the YAG wavelength. The minimum injected power required to ensure locking of the 100-kW oscillator output was 1 μW.

We have demonstrated that it is possible to accurately control one frequency of a pulsed, high power, singly resonant optical parametric oscillator (SRO)[1] by injecting frequency controlled radiation from a low powered source into a mode of the oscillator cavity. In particular, we have "locked" the frequency of of the short-wavelength resonated output of a ruby-laser-pumped $LiNbO_3$ SRO to that of a single-mode cw Nd:YAG laser. When radiation injection was used, oscillation repeatedly took place on a single axial mode of the oscillator cavity, the frequency of which had been previously adjusted to be equal to that of the injected radiation. Since the spectra of pulsed high-powered SRO's are not usually single axial mode nor exactly reproducible from shot-to-shot,[2] radiation injection could be a useful technique in applications where a high degree of frequency control is required.

The "locking" behavior which we will describe is to be differentiated from the frequency locking of one cw oscillator to another,[3] and might more properly be compared with the locking of two Q-switched lasers.[4] Our technique is limited to pulsed oscillators, and the injected radiation need only be present in the oscillator cavity when the pump is turned on. To clarify this point, consider the transient buildup of radiation in a pulsed SRO in which there is no injected radiation. When a pump wave exceeding threshold intensity is turned on, some of the resonant modes of the cavity see gain, and the radiation in them starts to build up exponentially from noise[5] (roughly 10^{-10} W per mode). The various modes build up at a rate which depends upon their degree of momentum mismatch Δk, those with smallest Δk building up most rapidly. Exponential buildup continues until the mode with highest gain (that closest to $\Delta k = 0$) starts to deplete the pump, whereupon a complicated process of settling down to steady-state oscillation ensues. If pumping is not too much in excess of threshold, single-mode steady-state oscillation on the mode closest to $\Delta k = 0$ presumably results.[6]

Now, assume that radiation is injected into a mode of the cavity at $\Delta k \neq 0$. When the pump is turned on, this radiation also starts to grow exponentially, but less rapidly than the mode nearest $\Delta k = 0$. Nonetheless, if the initial level of the injected mode is sufficiently large compared with the noise level, the injected mode starts to deplete the pump before the mode nearest $\Delta k = 0$ does. If the injected mode is considerably more intense than the mode nearest $\Delta k = 0$ at this time, the oscillator settles into quasi-steady-state oscillation on the injected mode, and the gain seen by the mode nearest $\Delta k = 0$ is greatly reduced due to pump depletion. However, this mode still experiences net positive gain and continues to build up.[6] Thus, after a period of time the mode nearest $\Delta k = 0$ will begin to challenge the injected mode for the pump power. Eventually it will take over and the injected mode will die out. Thus, the frequency control which we are describing is one that lasts for a limited period of time. Computation of the locking time is complicated and has not yet been completed. However, the empirical fact that we have been able to maintain locking for 10 nsec—the full length of the oscillator pulse—is encouraging.

The basic experimental setup is shown in Fig. 1. The single-mode ruby laser[7] and the basic SRO[1] were previously described. The orientation of the $LiNbO_3$ crystal was adjusted so that without injection the resonated output of the oscillator was in the vicinity of 1.06 μ, and the corresponding non-

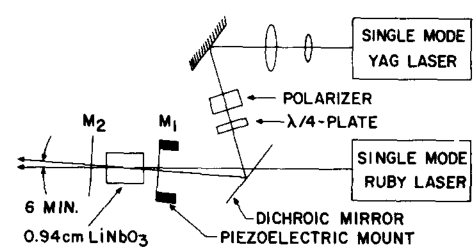

Fig. 1. Schematic diagram of the basic experimental setup. The flat mirrors M_1 and M_2 formed the oscillator cavity and were separated by about 1.4 cm. The two laser beams were collimated with diameters of about 2 mm and were made to overlap in the $LiNbO_3$ crystal. The YAG beam was normal to the oscillator mirrors.

resonant output was near 2.00 μ. The reflectivities of M_1 were 16.0 % at 0.6943 μ, 97.8 % at 1.064 μ, and 8.6 % at 2.00 μ; the corresponding reflectivities of M_2 were 12.0, 93.8, and 9.0 %. The cw, single longitudinal- and transverse-mode YAG laser was stabilized against frequency drift and intensity fluctuations.[8] Radiation injection was accomplished by using the piezoelectric mirror mount of M_1 to adjust the oscillator cavity length for resonance of the injected radiation. In this regard, the use of a SRO, as opposed to a doubly resonant oscillator (DRO), is important. For a SRO it is only necessary to resonate the injected radiation; if a DRO were used it would be necessary to adjust the cavity so that *both* the signal and idler radiations were resonant, a particularly difficult task since the ruby frequency is not exactly the same from shot-to-shot. An added advantage of the SRO is that the frequency of the resonated wave can remain locked even if the pump frequency changes during the pulse. The frequency of the nonresonant wave is free to compensate for such changes. While injection was maintained, the ruby laser was fired and the oscillator output was monitored in several ways.

For a 3-MW 15-nsec (FWHM) pump pulse, the maximum short-wavelength output power transmitted by M_2 was roughly 100 KW in a 5-nsec pulse. The long-wavelength output should have been substantially greater.[2] On a statistical basis definite enhancement of the output power due to radiation injection was observed. Enhancement occurs because the buildup time of the oscillator was comparable to the pump pulse width and steady-state oscillation was only approached, not achieved. Accurate quantitative evaluation of the enhancement was not possible due to shot-to-shot fluctuations in the ruby-laser power and the sensitivity of the oscillator output to such fluctuations. However, enhancement was not greater than a factor of 4.

The frequency of the short-wavelength output of the oscillator was compared with the frequency of the injected radiation using a Fabry–Perot interferometer in conjunction with an image converter. On all shots, irrespective of whether or not injection was used, the oscillator cavity was adjusted to be resonant for the YAG radiation. Figures 2(a) and 2(b) show comparisons of typical results obtained with and without injection using interferometers with free spectral ranges of 76 and 1.5 GHz, respectively. (The axial-mode spacing of the oscillator is about 5.8 GHz.) Without injection, oscillation usually took place on several axial modes (one of which might have corresponded to the YAG frequency) distributed over a range of several Å. With injection, however, oscillation usually took place only on the mode corresponding to the injected frequency. In cases where more than one mode was present, the injected mode was always the strongest. Time-resolved spectra were not obtained. Successful locking was achieved in about 90% of the attempts; various explanations, such as drift of

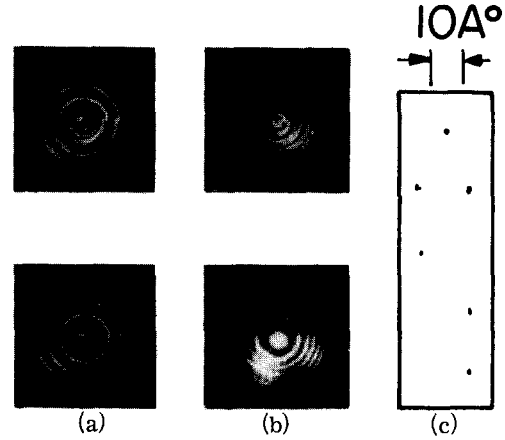

Fig. 2. (a) Interference fringes obtained with a 1.98-mm Fabry–Perot interferometer. The upper half of each ring system is of the YAG beam and the lower half is of the oscillator output. The upper ring system was obtained without injection and the lower was with injection. (b) Same as (a) but with a 10-cm interferometer spacing. (c) Artist's reproduction of spectra obtained using the spectrometer. The oscillator was adjusted so that without injection oscillation occured about 16 Å away from the YAG wavelength. Proceeding from top to bottom: oscillator without injection, with injection, without, with, YAG laser.

cavity resonances could be invoked to give plausible explanations of the failures. When radiation injection is successfully employed, the frequency of the short-wavelength oscillator output is expected to be the same as the frequency of the injected radiation. Data such as are shown in Fig. 2(b) demonstrate that the frequencies are equal to better than 25 MHz.

To investigate the frequency control on a coarser scale, we used a $\frac{3}{4}$-m spectrometer and Polaroid Type 413 infrared film to monitor the short-wavelength output of the oscillator with a resolution of about 0.5 Å. An example of such spectra is shown in Fig. 2(c).

The spectrometer was of particular use in determining the range over which radiation injection was effective in locking the oscillator. For approximately 10 mW of circularly polarized YAG radiation incident on the oscillator (only 0.6 of this amount, a linearly polarized component enhanced by a factor of 1.2 by the cavity resonance, is effective in producing locking) and a pump power of approximately 3 MW, successful locking was obtained if the peak of the oscillator gain curve was tuned to within 18 Å of the YAG wavelength on the short-wavelength side. A similar range would be expected for the long-wavelength side.

To determine the minimum amount of injected power required to produce locking, the oscillator was tuned to oscillate within several Å of the YAG wavelength and the injected power was reduced using one or two calibrated filters. The 10-cm Fabry–Perot interferometer was used to detect the absence of locking. For a pump power of approximately 3 MW, the minimum power for which locking was consistently obtained was approximately 2 μW of circularly polarized YAG radiation.

The above-measured numbers were compared with theory using a simple model like the one previously described. Basically, it was assumed that the oscillator modes experienced strictly exponential buildup from their initial levels (pump depletion was ignored) and that steady-state oscillation resulted on the first mode to reach 10% of the pump intensity. If this was the injected mode, locking occurred. This model indicated an expected locking range of ± 20 Å, in good agreement with the measured 18 Å. The calculated value for the minimum injected power was roughly 0.004 of the experimental value of 1 μW. However, this parameter is quite sensitive to changes in the operating conditions and a more realistic calculation is expected to give a result in much better agreement with the measured value.

Our experiments have shown that it is possible to lock one frequency of a high-power pulsed SRO to the frequency of a low-power source of coherent radiation. Unfortunately, accurately controlled, broadly tuneable, single-frequency sources are not presently available; thus, locking of the continuously tuneable SRO is temporarily restricted to the relatively few laser lines. In principle, a filtered broad-band source could also be used as the source of the injected radiation. However, a minimum "effective black-body temperature" of 4×10^8 °K would be required. Several approaches using pulsed lasers seem possible.[9-11] In the future one may hope to use highly stabilized, continuously tuneable, cw parametric oscillators as the source of control radiation.

One of the authors (J. E. Bjorkholm) is indebted to A. Ashkin for many discussions regarding frequency control of parametric oscillators. Both authors acknowledge the technical assistance of D. B. Pearson.

[1] J. E. Bjorkholm, Appl. Phys. Letters 13, 53 (1968).

[2] J. E. Bjorkholm, Appl. Phys. Letters 13, 399 (1968).

[3] H. L. Stover and W. H. Steier, Appl. Phys. Letters 8, 91 (1966).

[4] A. N. Bondarenko, K. G. Folin, V. A. Smirnov, and V. V. Antsiferov, Zh. Eksperim. i Teor. Fiz. Pis'ma v Redaktsiyu 6, 692 (1967) [English transl.: Soviet Phys.—JETP Letters 6, 178 (1967)]; also see A. N. Bondarenko, G. V. Krivoshchekov, and V. A. Smirnov, *ibid.* 9, 100 (1969)[English transl.: JETP Letters 9, 57 (1969)].

[5] W. H. Louisell, A. Yariv, and A. E. Siegman, Phys. Rev. 124, 1646 (1961).

[6] L. B. Kreuzer, to be published in "Proceedings of Conference on Lasers and Opto-Electronics," sponsored by Institution of Electronics and Radio Engineers, England, April, 1969.

[7] J. E. Bjorkholm and R. H. Stolen, J. Appl. Phys. 39, 4043 (1968).

[8] H. G. Danielmeyer (unpublished).

[9] S. E. Harris, M. K. Oshman, and R. L. Byer, Phys. Rev. Letters 18, 732 (1967); D. Magde and H. Mahr, *ibid.* 18, 905 (167).

[10] R. L. Carman, J. Hanus, and D. L. Weinberg, Appl. Phys. Letters 11, 250 (1967); M. D. Martin and E. L. Thomas, Phys. Letters 25A, 637 (1967).

[11] Fujio Shimizu, Phys. Rev. Letters 19, 1097 (1967).