

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 11/27/96	3. REPORT TYPE AND DATES COVERED Final Progress 8/1/93 - 9/30/96		
4. TITLE AND SUBTITLE Optical Frequency Counting and Synthesis		5. FUNDING NUMBERS DAAH04-93-G-0399		
6. AUTHOR(S) Dr. Ngai C. Wong				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Research Laboratory of Electronics Massachusetts Institute of Technology 77 Massachusetts Avenue Cambridge, MA 02139-4307		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211		10. SPONSORING / MONITORING AGENCY REPORT NUMBER ARO 31413.9-PH		
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12 b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words)		<p>A novel method of optical frequency counting and synthesis has been proposed based on a parallel network of optical parametric oscillators. The scheme utilizes the generation of precise frequency ratios by nonlinear optical techniques to phase lock a calibration optical frequency to the primary frequency standard at 9.2 GHz. By operating entirely in the visible to near-IR regions and taking advantage of advances in nonlinear crystals, detectors and modulators in this spectral region, an optical-to-microwave frequency chain can be operated efficiently and compactly. The proposed frequency chain can be used to provide the highest frequency accuracy in the visible for applications such as optical frequency standards, precision spectroscopy, and measurements of fundamental constants. Moreover, the method is applicable to producing a commercial optical frequency counter and synthesizer for use in laboratory and field environments. In addition, the proposed frequency counter can be used to provide accurate frequency markers in the important 1.55-μm optical communication band. The main focus of this work has been to develop the various technologies that are needed for a prototype optical frequency counting and synthesis apparatus.</p>		
14. SUBJECT TERMS		15. NUMBER OF PAGES		
		16. PRICE CODE		
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

FINAL REPORT

Optical Frequency Counting and Synthesis

U. S. Army Research Office
Grant DAAH04-93-G-0399

Covering the Period
August 1, 1993 - September 30, 1996

Submitted by

Ngai C. Wong
Principal Investigator

November 27, 1996

Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

19970213 049

Contents

1	Statement of Work	2
2	Research Summary	3
2.1	Optical Parametric Oscillator Technology	3
2.2	Nonlinear Optical Measurements	4
2.3	Optical-to-Microwave Frequency Chain	5
2.4	Outlook	6
	References	8
3	Personnel	10
4	List of Publications	11
5	List of Meeting Presentations	13
6	Patent	15

1 Statement of Work

A novel method of optical frequency counting and synthesis has been proposed based on a parallel network of optical parametric oscillators. The scheme utilizes the generation of precise frequency ratios by nonlinear optical techniques to phase lock a calibration optical frequency to the primary frequency standard at 9.2 GHz. By operating entirely in the visible to near-IR regions and taking advantage of advances in nonlinear crystals, detectors and modulators in this spectral region, an optical-to-microwave frequency chain can be operated efficiently and compactly. The proposed frequency chain can be used to provide the highest frequency accuracy in the visible for applications such as optical frequency standards, precision spectroscopy, and measurements of fundamental constants. Moreover, the method is applicable to producing a commercial optical frequency counter and synthesizer for use in laboratory and field environments. In addition, the proposed frequency counter can be used to provide accurate frequency markers in the important 1.55- μm optical communication band. The main focus of this work has been to develop the various technologies that are needed for a prototype optical frequency counting and synthesis apparatus.

2 Research Summary

Under ARO Grant DAAH04-93-G-0399 "Optical Frequency Counting and Synthesis," we have pursued a vigorous program of experimental research on optical frequency counting and its associated technologies. In this final report we shall summarize the principal results that we have obtained. Complete details can be found in the journal articles and meeting presentations that have been produced during the course of our research program.

2.1 Optical Parametric Oscillator Technology

An optical parametric oscillator (OPO) is a nonlinear optical device that converts an input pump into two subharmonics whose frequency sum equals the pump frequency. OPOs are highly efficient and are tunable over a broad spectral range, making them a superior tunable light source [1]. OPOs play an important role in this research program as highly stable and precisely tunable optical frequency dividers [2, 3, 4]. We have developed a number of techniques to improve the stability and tunability of cw doubly resonant OPOs.

In a doubly resonant OPO the optical cavity is resonant with the signal and idler waves simultaneously and therefore the OPO is in general not very stable. We have developed a dual-cavity OPO in which the orthogonally polarized signal and idler are internally separated by a polarizing beam splitter so that each subharmonic wave is resonated in its own separate cavity. In this way, the signal and idler cavities can be individually tuned and therefore continuous frequency tuning becomes feasible. We demonstrated a dual-cavity OPO with a continuous tuning range of 1 GHz, about a 100-fold improvement relative to a single-cavity OPO [5].

In the study of the dual-cavity OPO, we have noted the possibility of mixing

the orthogonally polarized signal and idler waves by use of a polarization-sensitive intracavity element [5]. Subsequently we have developed a self-phase locked type-II phase-matched OPO that takes advantage of this mechanism for polarization mixing. By inserting a quarter-wave plate in the optical cavity, the signal and idler waves experience a polarization rotation after passing through the waveplate twice in a cavity roundtrip. In this way, their polarizations are mixed and this provides a means for self-injection locking when the OPO is operated near frequency degeneracy. We have observed self-phase locking to occur when the frequency separation between the signal and idler is less than 300 MHz and the self-phase locked OPO was found to be stable [6, 7]. This is the first time that self-phase locking in a type-II phase matched OPO has been demonstrated. This technique is particularly useful in optical frequency division because it eliminates the use of complicated servo locking circuits and the self-phase locked OPO is more stable than our previous externally phase locked OPOs [3].

2.2 Nonlinear Optical Measurements

We have made a number of new measurements that provide useful information on the phase noise of an OPO and on a new crystal cesium titanyl arsenate. For optical frequency counting, an OPO frequency divider should have very low phase noise in order that the optical-to-microwave frequency chain can be phase coherent. In an externally phase locked OPO at a signal-idler beat frequency of 30 MHz, we demodulated the beat signal and measured the in-phase and quadrature-phase phase noise and compared with our theoretical estimates [8, 5]. We have observed for the first time the phase diffusion noise of an OPO that is far above the shot noise level at low rf frequencies, as expected. This work lays the foundation for further investigation

into the control and study of the fundamental noise limit of an OPO for use in high precision measurements.

We have made difference-frequency measurements in a cesium titanyl arsenate (CTA) crystal that is an isomorph of KTP [9, 10]. CTA is type-II phase matched, has a large temperature bandwidth, and is phase matchable at wavelengths longer than KTP. In particular, noncritical phase matching is possible for the interaction: $798 \text{ nm} + 1596 \text{ nm} \rightarrow 532 \text{ nm}$, which has a 3:1 frequency ratio. By using inputs from a krypton ion laser at 531 nm and a tunable Ti:sapphire laser centered at 800 nm, we obtained tunable radiation from 1.57 to 1.65 μm with a single-pass output power of 1 μW . When the system was configured as a doubly resonant cavity, 100 μW of output power was obtained. We have thus verified the phase matching angle of CTA for 3:1 frequency division and also determined its effective nonlinear coefficient at 2.30 pm/V.

2.3 Optical-to-Microwave Frequency Chain

In 1992 we proposed to realize an optical-to-microwave frequency chain by use of a parallel network of OPOs that are related at some fixed frequency ratios. The method should allow one to accurately measure any optical frequency from the UV to the near-IR relative to the Cs primary frequency standard [11]. This scheme is rather complicated requiring many stages of OPOs operating in unison. It is therefore useful to devise a simpler and more accessible system to realize an optical frequency chain with the same advantages of operating only in the visible and near-IR spectral regions. By utilizing a second calibration laser, we have proposed a new method of achieving optical frequency counting by using fewer number of OPOs and by generating a frequency ratio of (4/9) [12].

A 3:1 frequency divider can be realized in the following way. The first step is to generate from a 3ω input pump two outputs $2\omega + \delta$ and $\omega - \delta$. Difference-frequency mixing for the two outputs then yields $\omega + 2\delta$. By measuring the beat frequency 3δ between $\omega - \delta$ and $\omega + 2\delta$ and setting $\delta = 0$, an exact 3:1 frequency ratio is obtained [13].

In the new scheme of a two-laser OPO network, a doubled-YAG 532-nm pump at ω generates a $(2/3)\omega$ output at 798 nm, to which a second laser is phase locked. This second laser pumps another OPO to generate an output at a $(2/3)$ frequency ratio at 1197 nm. This output frequency is exactly equal to $(4/9)\omega$. By measuring the frequency difference between the $(4/9)\omega$ and $(1/2)\omega$ (YAG laser), which is ~ 31 THz, relative to the Cs clock, ω is absolutely determined. The difference frequency measurement can be made by using a set of ~ 5 OPOs in parallel and by employing terahertz optical frequency combs [14].

2.4 Outlook

Together with research performed under other programs, we have investigated and demonstrated a number of important technologies that bring us to the threshold of demonstrating a two-laser based optical-to-microwave frequency chain. Under this grant, we have measured the phase noise of an OPO and demonstrated a novel self-phase locked OPO. A dual-cavity OPO has been shown to offer great promise as a continuously tunable light source. We have also studied the phase matching characteristics of a CTA crystal for 3:1 frequency division.

Under other research programs, we have now demonstrated terahertz optical frequency comb generation with a span of 4.3 THz which suggests that difference-frequency measurements at several THz is now feasible. We are fabricating peri-

odically poled lithium niobate (PPLN) wafers that can be quasi-phase matched for nonlinear frequency conversion at user-specified wavelengths. This solves an important material problem in the realization of an optical frequency chain that requires the generation of many optical frequencies at various spectral regions. We have also built a tunable diode laser and injection locked diode amplifier with an output power of 500 mW at 790 nm that serves as the second laser in our scheme. The diode laser system replaces the Ti:sapphire system we used earlier and makes it possible to obtain a compact all-solid-state system. We have high hopes that further work in this area will yield tremendous improvement in our optical frequency measurement and synthesis capability for a variety of applications in commercial, research, and military ventures.

References

- [1] R. L. Byer, in *Quantum Electronics: A Treatise*, H. Rabin and C. L. Tang, eds. (Academic, New York, 1975), pp. 587–702.
- [2] N. C. Wong, “Optical frequency division using an optical parametric oscillator,” *Opt. Lett.* **15**, 1129–1131 (1990).
- [3] D. Lee and N. C. Wong, “Tunable optical frequency division using a phase-locked optical parametric oscillator,” *Opt. Lett.* **17**, 13–15 (1992).
- [4] D. Lee and N. C. Wong, “Stabilization and tuning of a doubly resonant optical parametric oscillator,” *J. Opt. Soc. Am. B* **10**, 1659–1667 (1993).
- [5] Dicky Lee, “Optical parametric oscillators and precision frequency measurements,” Ph.D. thesis, M.I.T., 1996.
- [6] Elliott J. Mason, “Self-phase locking in a type-II phase matched optical parametric oscillator,” master thesis, M.I.T., 1996.
- [7] N. C. Wong, E. Mason, and P. Nee, “Metrological applications of frequency conversion in $\chi^{(2)}$ media,” *Quantum Semiclass. Opt.*, to appear.
- [8] D. Lee and N. C. Wong, “Quantum phase diffusion noise measurements in a cw optical parametric oscillator,” *Coherence and Quantum Optics VII*, Eberly, Mandel, and Wolf, eds., (Plenum Press, 1996), pp. 423–424.
- [9] B. Lai, N. C. Wong, and L. K. Cheng, “Continuous-wave tunable light source at 1.06 μm by difference-frequency mixing in CsTiOAsO_4 ,” *Opt. Lett.* **20**, 1779–1781 (1995).

- [10] Bobby Y. F. Lai, "A tunable light source at 1.6 μm by difference-frequency mixing in cesium titanyl arsenate," master thesis, M.I.T., 1995.
- [11] N. C. Wong, "Optical frequency counting from the UV to the near IR," *Opt. Lett.* **17**, 1155-1157 (1992).
- [12] N. C. Wong, "Optical-to-microwave frequency chain utilizing a two-laser-based optical parametric oscillator network," *Appl. Phys. B* **61**, 143-149 (1995).
- [13] N. C. Wong, B. Lai, P. Nee, and E. Mason, "Experimental progress toward realizing a 3:1 optical frequency divider," *Proceedings Fifth Symposium on Frequency Standards and Metrology*, Bergquist, ed., (World Scientific, 1996), pp. 319-326.
- [14] L. R. Brothers, D. Lee, and N. C. Wong, "Terahertz optical frequency comb generation using a resonant phase-velocity-matched electro-optic modulator," *Opt. Lett.* **19**, 245-247 (1994).

3 Personnel

Research under Contract DAAH04-93-G-0399 was carried out by:

Dr. Ngai C. Wong, Principal Investigator

Dicky Lee, Graduate Student

Ph.D., Physics, MIT, February 1996

Bobby Lai, Graduate Student

S.M., Electrical Engineering & Computer Science, MIT, January 1995.

4 List of Publications

The following journal articles report research performed under Grant DAAH04-93-G-0399:

1. L. R. Brothers, D. Lee, and N. C. Wong, "Terahertz optical frequency comb generation and phase locking of an optical parametric oscillator at 665 GHz," *Opt. Lett.* **19**, 245-247 (1994).
2. N. C. Wong, "Optical-to-microwave frequency chain utilizing a two-laser-based optical parametric oscillator network," *Appl. Phys. B* **61**, 143-149 (1995).
3. B. Lai, N. C. Wong, and L. K. Cheng, "Continuous-wave tunable light source at 1.06 μm by difference-frequency mixing in CsTiOAsO_4 ," *Opt. Lett.* **20**, 1779-1781 (1995).
4. D. Lee and N. C. Wong, "Quantum phase diffusion noise measurements in a cw optical parametric oscillator," *Coherence and Quantum Optics VII*, Eberly, Mandel, and Wolf, eds., (Plenum Press, 1996), pp. 423-424.
5. N. C. Wong, B. Lai, P. Nee, and E. Mason, "Experimental progress toward realizing a 3:1 optical frequency divider," *Proceedings Fifth Symposium on Frequency Standards and Metrology*, Bergquist, ed., (World Scientific, 1996), pp. 319-326.
6. N. C. Wong, E. Mason, and P. Nee, "Metrological applications of frequency conversion in $\chi^{(2)}$ media," *Quantum Semiclass. Opt.*, to appear.

7. D. Lee and N. C. Wong, "Tuning characteristics of a cw dual-cavity KTP optical parametric oscillator," in preparation.
8. E. J. Mason and N. C. Wong, "Self-phase locking in a type-II phase matched optical parametric oscillator," in preparation.

5 List of Meeting Presentations

The following meeting presentations reported research performed under Grant DAAH04-93-G-0399:

1. N. C. Wong, D. Lee, and L. R. Brothers, "Optical frequency counting based on parametric downconversion," Digest of International Symposium on Atomic Frequency Standards and Coherent Quantum Electronics, Nara, Japan, August 1993, pp. 14-17.
2. D. Lee, N. C. Wong, and L. R. Brothers, "Frequency tuning and stabilization of a KTP optical parametric oscillator," Digest of Optical Society of America Annual Meeting, Toronto, Canada, October 1993, p. 85.
3. N. C. Wong, D. Lee, and L. R. Brothers, "Continuous-wave phase-locked optical parametric oscillator as a tunable source for terahertz radiation," SPIE Proceedings of Nonlinear Optics for High-Speed Electronics, Los Angeles, CA, January, 1994, vol. 2145, pp. 190-199.
4. N. C. Wong and D. Lee, "Frequency tuning and phase locking of an ultrastable doubly resonant optical parametric oscillator," Optical Society of America Proceedings on Advanced Solid-State Lasers, Salt Lake City, UT, February 1994, pp. 432-434.
5. N. C. Wong, D. Lee, and L. R. Brothers, "Optical frequency measurement and synthesis using nonlinear optical techniques," Digest of Conference on Lasers and Electro-Optics, Anaheim, CA, May, 1994, p. 200.

6. D. Lee and N. C. Wong, "Tuning characteristics of a cw dual-cavity KTP optical parametric oscillator," Digest of Conference on Lasers and Electro-Optics, Anaheim, CA, May, 1994, pp. 200-201.
7. D. Lee and N. C. Wong, "Quantum phase diffusion noise measurements in a cw optical parametric oscillator," Proceedings of Coherence and Quantum Optics VII, Eberly, Mandel, and Wolf, eds., (Plenum Press, 1996), pp. 423-424.
8. N. C. Wong, B. Lai, P. Nee, and E. Mason, "Experimental progress toward realizing a 3:1 optical frequency divider," Proceedings of Fifth Symposium on Frequency Standards and Metrology, Bergquist, ed., (World Scientific, 1996), pp. 319-326.
9. N. C. Wong, E. Mason, and P. Nee, "Metrological applications of frequency conversion in $\chi^{(2)}$ media," Les Houches Workshop on Second Order Nonlinear Optics: from Fundamentals to Applications, Les Houches, France, April 1996.
10. E. J. Mason and N. C. Wong, "Self-phase locking in a type-II phase-matched optical parametric oscillator," submitted for presentation at Conference on Lasers and Electro- Optics, Baltimore, MD, May 1997.

6 Patent

1. Ngai C. Wong, "Optical Frequency Counter/Synthesizer Apparatus," U.S. Patent No. 5,233,462, issued Aug. 3, 1993.