

Cavity-Dumped Communication Laser Design

W. T. Roberts¹

Cavity-dumped lasers have significant advantages over more conventional Q-switched lasers for high-rate operation with pulse position modulation communications, including the ability to emit laser pulses at 1- to 10-megahertz rates, with pulse widths of 0.5 to 5 nanoseconds. A major advantage of cavity dumping is the potential to vary the cavity output percentage from pulse to pulse, maintaining the remainder of the energy in reserve for the next pulse. This article presents the results of a simplified cavity-dumped laser model, establishing the requirements for cavity efficiency and projecting the ultimate laser efficiency attainable in normal operation. In addition, a method of reducing or eliminating laser dead time is suggested that could significantly enhance communication capacity. The design of a laboratory demonstration laser is presented with estimates of required cavity efficiency and demonstration potential.

I. Introduction

Optical communications experiments from space are demonstrating very significant payoffs in data rates and efficiency. The European Space Agency (ESA) Advanced Relay and Technology Mission (Artemis) link has demonstrated a stable 50 Mb/s link from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO) [1,2]. For years, mission designers have dreamed of applying this communication technology to overcome the data transmission bottleneck currently limiting the instrumentation of interplanetary probes [3,4]. The goal of the JPL Optical Communications Group is to develop the technology that will allow those high data transmission rates to be realized, and to enable the next generation of interplanetary probes to make full use of the high-resolution instruments in development.

To achieve this goal, laser technology is being developed that can support 10- to 100-Mb/s data transmission rates at deep-space [>1 astronomical unit (AU)] ranges. While a modulated diode laser is adequate for communication in the near-Earth region [1], the vast distances involved in interplanetary missions require lasers that are capable of emitting much more energetic pulses. To achieve the demonstration goal of 10 Mb/s from Mars, our system design hypothesizes a laser that, under the most stressing conditions, emits up to 8 μJ per pulse at average rates of $1.5 \times 10^6 \text{ s}^{-1}$, with variable pulse-to-pulse spacing to encode the data in an energy-efficient pulse position modulation (PPM) format. This must be done with materials and components that are suitable for long space-flight missions and with technology that has a development path to relatively high electrical efficiency (>10 percent).

¹ Communications Systems and Research Section.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Much previous work has concentrated on Q-switched solid-state lasers (e.g., [5,6]) and recently on master oscillator power amplifier (MOPA) systems (e.g., [7–11]). Both of these show promise in various applications but still face challenges in development for these particular goals. With Q-switched lasers, the biggest hurdle is in achieving high pulse-repetition rates [12, pp. 452–483]. As a Q-switch is pulsed faster and faster, the level of gain achievable at a given pump intensity is reduced, leading to longer output pulses and lower efficiency. Pulse emission rates over 100 kHz have been demonstrated, but with diminishing suitability for deep-space data transmission. Other problems with Q-switched lasers are the pulse buildup time and timing jitter, the dead-time constraint for pumping the gain medium, and the inability to control the emitted fraction of stored energy.

The advantage of the MOPA is its potential for use with simple, efficient diode laser modulation, which has a legacy from other space-based laser communication systems [1]. From a practical standpoint, by decoupling the pulse generation system from the pulse amplifier, the development of a deep-space communication system based on MOPAs should be much more straightforward. In addition, the potential of fiber amplifiers is particularly intriguing in that they are efficient, lightweight, require little or no cooling, require little alignment, and are amenable to remote location of the light-generating source from the transmitter system. However, there are still concerns to be addressed in MOPA designs. First, suppression of amplified spontaneous emission (ASE) is required to maintain the gain of the amplifier and prevent the emission of spurious signals. Second, as with Q-switched lasers, the pulse delay and pulse timing jitter must be characterized and controlled. Amplifier pulse dispersion (spectral and temporal) is also of concern. Control of the output pulse power is limited to controlling the gain of the amplifier through pump modulation, leaving little room for maintaining energy in the amplifier for a second pulse emitted shortly after the first. Finally, stimulated Raman scattering (SRS) and, to a lesser extent, stimulated Brillouin scattering (SBS) and self-phase modulation (SPM) limit the peak power attained from fiber MOPAs, limiting the ability of those systems to operate at ranges beyond 2 AU [13].

For the high modulation rates and peak powers desired, a cavity-dumped laser is in many ways more suitable as a laser source [14–17]. Like a Q-switched laser, a cavity-dumped laser makes use of a gain medium in a cavity with an intracavity light modulator, such as an electro-optic modulator (EOM). The main differences are in the operation of the system [13, pp. 494–499]. With a Q-switch, the cavity is held in an inefficient state (spoiled) by the EOM to prevent the oscillation of an electric field that depletes the gain through stimulated emission. When the gain is finally built up to a desired level, the cavity efficiency is changed and the gain is rapidly converted into an oscillating optical field and emitted in the form of an intense, short pulse. In cavity-dumping, the cavity is maintained in a very efficient state such that the optical field is built up to some desired level. One way of doing this is to use a variable output coupler, in which the output coupler is switched on and off to minimize the losses during the wave buildup phase. Thus, the energy is stored in the oscillating optical field instead of in the gain medium.

Conversion to a cavity-dumped system offers three main advantages. First, there is practically no pulse delay or pulse jitter. The pulse output is controlled by the EOM, which generates the output coupling of the laser within the short (<1-ns) switching time of the EOM. Second, the optical field can be partially coupled out, retaining a variable fraction of the energy within the cavity. This is particularly advantageous for a Mars-link mission, in which ranges vary by a factor of five. Larger fractions of the oscillating optical field can be coupled out to generate more energetic pulses as the Mars–Earth distance increases. Finally, by retaining energy in the cavity, the buildup time required before the next pulse can be reduced or even eliminated altogether. Maintaining this field within the cavity comes at the cost of reduced efficiency, however.

Achieving a design of a cavity-dumped laser to meet these challenging requirements still faces hurdles, however. One constraint that must be met is that the materials and surfaces in the cavity must be capable of withstanding the repeated high-intensity pulses inherent in the design. A rapid, efficient EOM is required to activate the output coupling over the very short (\sim 1-ns) time periods of the output pulse. Finally, a critical element of the design will be to develop an extremely low-loss cavity that will allow the

efficient accumulation and storage of energy. As an alternative approach, the same cavity configuration can be used in a hybrid Q-switched cavity-dumped mode, in which the energy is initially stored in the gain medium for rapid conversion to the optical field prior to cavity dumping. This is useful because the gain medium is generally a more efficient long-term storage device than the optical cavity.

II. Cavity-Dumped Laser Model

A model of a cavity-dumped laser was developed to have a tool for investigating the cavity efficiency required to obtain the pulse energy for a laser operating as a PPM communication source. It also was developed for determining the effective dead time required to build up the pulse energy under various conditions. Furthermore, the model can be used to estimate the total efficiency that such a laser might achieve.

A proper treatment of the laser model must allow for the buildup and subsequent depletion of the gain in the laser medium [12, pp. 494–499]. To do this, the model should keep track of γ and n , the number of laser photons in the cavity and the number of lasing atoms in the excited state of the gain medium, respectively. This is done with the laser rate equations:

$$\frac{dn}{dt} = \eta_p \eta_q P \frac{2l_{cav}}{c} \frac{\lambda}{hc} \frac{n_{tot} - n(t)}{n_{tot}} - \frac{2l_{cav}n(t)}{c\tau_f} - \frac{\sigma_{se}}{\pi r^2} n(t)\gamma(t) \quad (1)$$

governing the rate of change of excited neodymium (Nd) atoms and

$$\frac{d\gamma}{dt} = \frac{\sigma_{se}}{\pi r^2} n(t)\gamma(t) - (1 - \eta_{cav})\gamma(t) \quad (2)$$

governing the buildup of laser photons in the cavity, where

- n = the number of excited Nd atoms
- γ = the number of lasing photons in the cavity
- t = time
- η_p = pump efficiency
- η_q = photon conversion quantum efficiency
- η_{cav} = the round-trip cavity photon recirculation efficiency
- P = the pump power
- l_{cav} = the unidirectional cavity optical length
- c = the speed of light constant (3×10^8 m/s)
- h = Planck's constant (6.626×10^{-34} J s)
- λ = the pump photon energy
- n_{tot} = the total number of Nd atoms in the lasing mode
- τ_f = the Nd atom fluorescence lifetime
- σ_{se} = the Nd atom stimulated emission cross section
- r = the lasing-mode radius

In Eq. (1), the first term on the right-hand side represents the pump rate of Nd atoms to the excited state subject to saturation, the second term is the loss of these atoms from the excited state resulting from spontaneous emission, and the final term represents the loss of excited-state Nd atoms through stimulated emission. In the second equation, the first term is the increase to the photon field in the cavity as a result of stimulated emission, while the second term is the general loss per round-trip pass of photons held in the cavity.

Figure 1 shows the number of excited Nd atoms (n in blue) and the number of intracavity photons (γ in red) per round-trip pass of the cavity. The gain is observed to increase linearly at first, slowly rolling off as a result of saturation, while the photon field remains relatively low. At a point determined by the cavity efficiency and the relative gain state, the photon field begins to build up rapidly, depleting the gain through stimulated emission and efficiently converting the stored gain into intracavity photons. The gain is reduced to roughly the level at which gain clamping would occur in the laser if operated in the continuous wave (CW) condition. As long as the photon field is maintained at a high state, the gain cannot build up beyond this because of the high probability of stimulated emission loss to the photon field. Additional pump power is almost immediately converted to photon energy in the field. While this conversion is a relatively efficient process, maintaining the photon field at a high state for many passes is not, because of the unavoidable, fixed photon loss per cavity round-trip.

If, near the point of maximum photon number, enough of the intracavity energy is ejected in a PPM pulse to reduce the photon field below the level where stimulated emission dominates the rate equations, the gain medium can once again be used to store energy for the next pulse. However, if a relatively large photon field is maintained in the cavity, the effect of gain storage is minimal, as shown in Fig. 2. In this case, $2\mu J$ of energy are maintained in the cavity after pulse emission, allowing the gain to initially increase only slightly before rapidly losing its stored energy to the rising photon field. Note also in this case that the maximum achievable photon-field intensity is reduced because of the inferior long-term storage of photons.

Based on these results, a simplified model was developed to estimate an upper bound to the cavity losses. This was done by assuming that sufficient photon field is retained after a pulse that further pump power is transferred almost immediately to the photon field, rather than building up appreciable gain. Because of the relative inefficiency of photon storage compared to gain storage, the losses of this model represent the maximum likely loss for a given set of operating conditions (e.g., pump power, cavity efficiency, etc.). As a starting point, 40 W of optical power were assumed from the pump diodes, of which 80 percent might be absorbed in a useful lasing mode. Applying the Nd quantum efficiency of 0.75 leaves 24 W of possible cavity power at 1064 nm. Thus, within a 10-ns round-trip cavity time (corresponding to a laser cavity length of roughly 1.5 m), as much as $0.24\ \mu J$ might be added to the photon field.

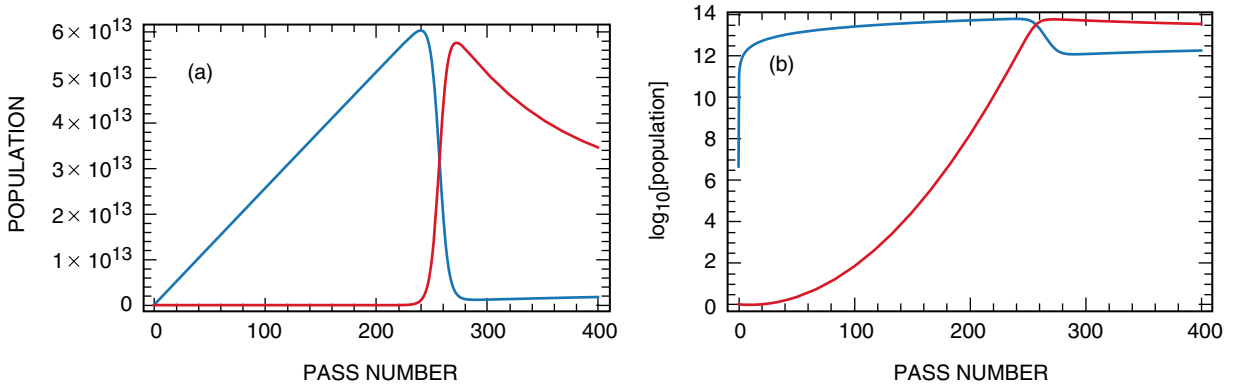


Fig. 1. Buildup of gain (blue curve) and photon density (red curve) as a function of the number of passes through the cavity, shown on a (a) linear scale and (b) logarithmic scale.

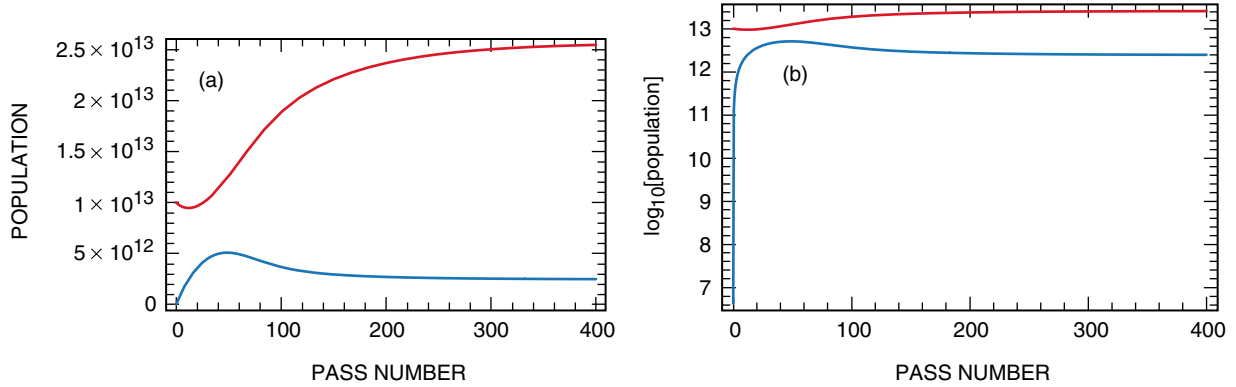


Fig. 2. Buildup of gain (blue curve) and photon number (red curve) on a (a) linear scale and (b) logarithmic scale, assuming that $2 \mu\text{J}$ of energy are retained in the cavity after the previous pulse is emitted.

After many passes, the pulse energy asymptotically approaches a value determined by the useful pump power and the cavity efficiency. As an example, Fig. 3 shows the growth of the pulse energy and cumulative lost energy after a number of cavity round-trips, assuming that the cavity round-trip efficiency is 97 percent (red), 98 percent (blue), and 99 percent (green). The solid lines are the amount of energy in the circulating pulse, while the dashed lines indicate the cumulative loss since the beginning of this cycle.

The pulse clearly builds up more quickly with the 99 percent efficient cavity, reaching the $8\text{-}\mu\text{J}$ requirement after about 40 passes. At this point, roughly $1.7 \mu\text{J}$ has been lost from this cavity. As the cavity efficiency drops to 98 percent, 55 passes are required to build up to the communication threshold, during which $5.2 \mu\text{J}$ have been wasted. For a cavity that is only 97 percent efficient, the pulse energy asymptotically approaches the $8\text{-}\mu\text{J}$ requirement, and the wasted energy exceeds the stored pulse energy before $6.5 \mu\text{J}$ have built up in the pulse. Such a design, if implemented, would have to overcome these deficiencies by implementing gain storage or increasing the pump power.

III. System Examples

Using the simplified model, the requirements for the first-order design of the cavity-dumped laser were derived. To evaluate the potential of this laser in the most stressing conditions, a point design link from Mars at 2.5 AU was considered. Link analysis indicates that, in the worst conditions (full range, highest backgrounds, etc.), output pulses of $8 \mu\text{J}$ are needed, emitted at an average rate of 1.5×10^6 pulses per second. The cavity efficiency needs to be around 97.6 percent (Fig. 4) to meet the requirement to build up a pulse from zero within the 670 ns required for a 1.5-MHz word rate.

This is the most stressing link considered, which will be a relatively rare occurrence. Under this point design, more than 85 percent of the communication time would be spent operating at energies of less than $3 \mu\text{J}$ per pulse. As seen in Fig. 5, even a 95 percent efficient laser cavity is capable of reaching this reduced threshold in fewer than 20 passes, significantly reducing the dead time between pulses and allowing higher data rates.

A. Variation of Pump Power

If the pump diode power can be modulated at roughly the word output rate (1.5 MHz) from 50 percent of nominal to 100 percent, and if our cavity efficiency is 99 percent, the buildup times and consequent cumulative losses for 50, 75, and 100 percent of the maximum 40-W input pump are as shown in Fig. 6.

As expected, the buildup time is significantly reduced for higher pump powers, at 40 round-trips for 100 percent, 58 round-trips for 75 percent, and 109 round-trips for 50 percent pump power. Each of these

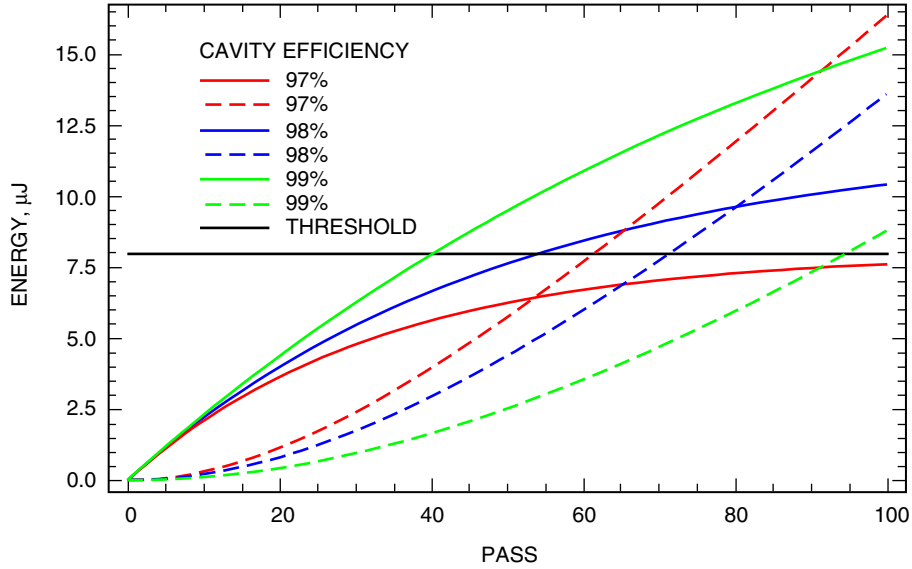


Fig. 3. Cavity energy buildup (solid) and cumulative losses (dashed) as a function of cavity round-trips.

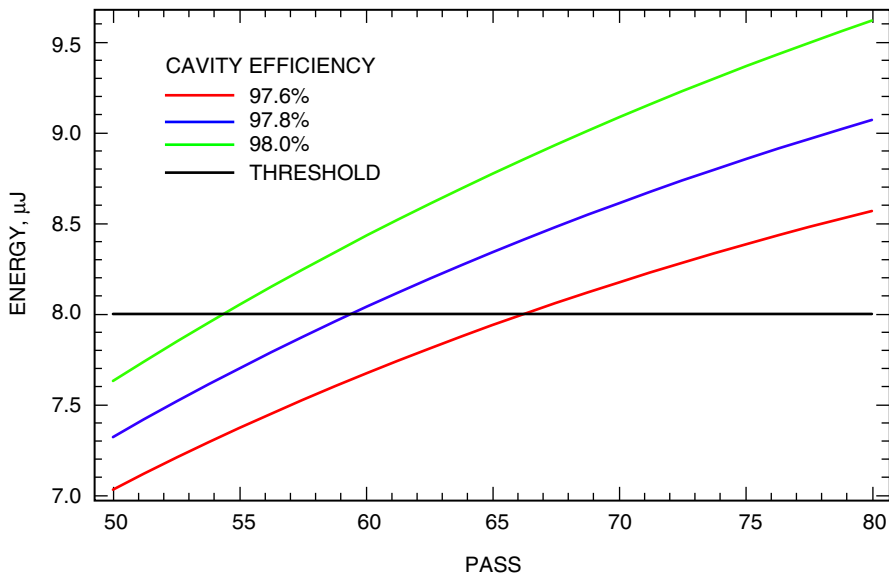


Fig. 4. The number of cavity round-trip passes required to reach the most stressing condition of link design. Lower cavity efficiency implies more time to build up the required pulse.

assumes the pulse is building up from zero. Although the overall loss rate is lower for the lower pump power, using the time to reach the $8\text{-}\mu\text{J}$ communication threshold as the metric, the slower pump rates result in higher lost power because of the need to go through many more cavity passes. At 100 percent pump power, the energy lost is only $1.75\ \mu\text{J}$ by the $8\text{-}\mu\text{J}$ threshold, while for the 75 and 50 percent pump power levels, the lost energy is $2.58\ \mu\text{J}$ and $5.12\ \mu\text{J}$, respectively. The implication of this is clear: to the extent possible, the pump should be held at a low level, and then driven up to its maximum rate in just enough time to reach the communication threshold. If the pump laser cannot accommodate rapid changes, then the lowest power should be used to reach the communication threshold.

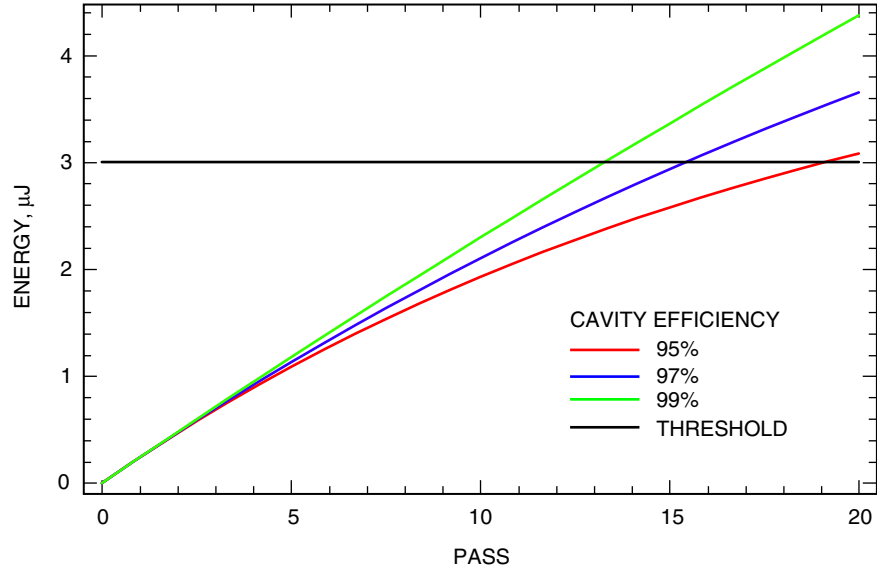


Fig. 5. Cavity efficiency is not as important in pulse buildup time for the majority of communication scenarios.

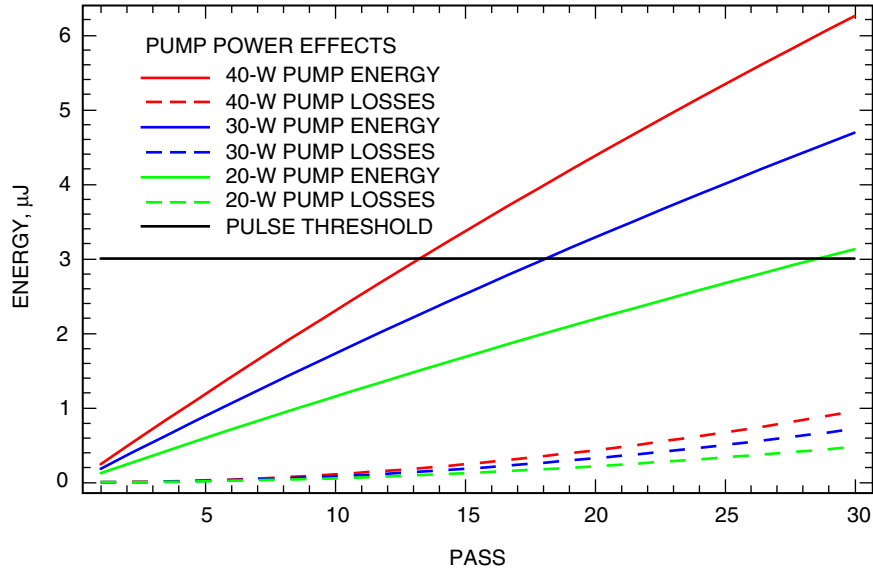


Fig. 6. Pulse energy (solid) and cumulative cavity losses as a function of round-trip cavity passes.

Operation in this mode incurs other inefficiencies, however. The ability of the system to efficiently switch amps of current to the pump diode must be explored. In actual operation, when emitting two widely separated pulses, it is probably more efficient to hold off lasing by setting the cavity in a spoiled state initially and allowing gain to build up (Q-switching). The amount of time required for the cavity wave to build up is inversely related to the amount of gain stored in the laser crystal, so that significantly less loss occurs. This hybrid Q-switching/cavity-dumping approach is beyond the scope of this initial treatment, but nevertheless is expected to be the implemented form of the flight laser on future missions.

B. Overcoming Dead Time

The previous analyses considered the buildup time required for a pulse of a given energy, but this assumes the pulses come regularly at the mean pulse rate. Since the information is coded in the particular position of the pulse with respect to the start of the symbol, the pulse temporal separation will vary from this mean value. Under the conditions considered so far in which the entire pulse is emitted, the system must impose a dead-time constraint on the transmission during which the next pulse must build up to the required energy. This constraint limits the pulse rate (and hence the data rate) as well as the system's overall efficiency.

The data throughput of the system is strongly dependent on the ratio of dead time to slot time, and on the PPM order, as shown in Fig. 7. Reduction of dead time obviously always improves data transmission rate, but often by more than just the dead-time factor. This is because as dead time is reduced, additional data-rate gains are obtained by going to lower-order PPM. As an example, for a laser operating with a dead-time that is roughly 1000 times longer than the slot time (typical of a Nd:YAG Q-switched laser), the optimal data throughput is achieved at 8-bit PPM (256 slots). This is shown in the lowest line of Fig. 7. By reducing the dead-time ratio from 1000 to 10 (dark blue line), throughput is increased by 7 dB at 8 PPM. However, for a dead-time ratio of 10, the optimum PPM order is 3 (8 slots), and an overall data rate increase of 14 dB is possible.

As shown earlier, the mean buildup time between words for the example system is about 640 ns. Because of the energy requirement on pulse emission, this normally would be imposed as a dead time during which adequate laser emission is not possible. However, this buildup time assumes that the field is building up from zero. Through judicious use of the electro-optical modulator, controlled fractions of the circulating power can be emitted, allowing the remainder to continue circulating through the cavity for future use. Assuming the cavity has the ability to build up to more than twice the required pulse energy, the dead-time constraint can be eliminated by retaining the energy required for the second pulse. Of course, this results in reduced energy efficiency because the losses are proportional to the energy stored in the cavity.

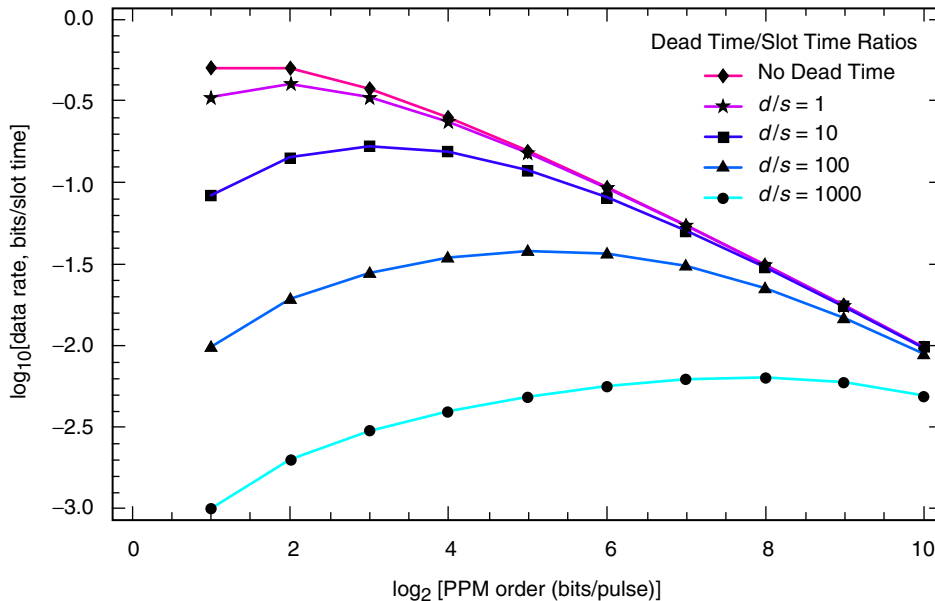


Fig. 7. Reduction of dead time relative to slot time results in large gains in channel capacity and drives the system to operate at lower-order PPM.

Assuming there is no dead time, the pulse-to-pulse time interval of the previous example will vary according to a triangle distribution with a mean of 640 ns, ranging from 10 ns in the most stressing case to 1.28 μ s. Since the transmitter knows a priori what the pulse sequence is to be, it is possible to plan ahead so that the power on the pump diodes is ramped up in anticipation of two closely spaced pulses to meet the buildup time, and ramped back down in anticipation of two widely spaced pulses to save power. In the worst cases, the power of the pulse cannot be built up in time to support two pulses spaced at 10 ns, imposing a dead-time constraint. However, this can be overcome again by advanced planning. In this case, as shown in Fig. 8, the power level is ramped up two pulses ahead, and the intracavity pulse energy is allowed to build up to 16 μ J. When coupling out the first pulse, the EOM is only partially activated, switching the polarization just enough to couple out 50 percent of the circulating pulse, or 8 μ J, allowing the remaining 8 μ J to continue to circulate. That remaining power then is available for the next pulse 10 ns later. In order for this situation to occur (two very closely spaced pulses), the first pulse must be emitted near the end of the word, guaranteeing time to build the pulse up to the higher level. Of course, this generates extra loss but, depending on the PPM order, the occurrence is infrequent.

The proper way of approaching this problem is to consider the problem from the end, and work backwards to determine the optimum pump rate and pump timing. As an example, assume a frame consisting of 10 words of 6 bits (64 slots) each. An example frame would be the sequence {46,21,56,45,12,62,3,46,48,22}. With direct encoding (i.e., 0 \rightarrow first slot of 64, 1 \rightarrow second slot of 64, \dots , 63 \rightarrow 64th slot of 64), the above sequence would have gaps (strings of zero pulse) of {46,38,98,52,30,113,4,106,65,37,41}. Note that this string contains a very stressing sequence of values, with a gap of only 4 slot periods between the emission of the pulse indicating a value of 62 and the pulse indicating a value of 3. However, in most cases there will be relatively long periods both before and after the pulse, allowing for a high buildup to the double pulse and a relatively long recovery period after the pulse. The result, assuming constant pumping at full power and continuous pulse buildup, is seen in Fig. 9.

With the example pulse train, it is clear that there is sufficient pulse energy for the most stressing communication requirement after each of the pulses. Even in the case of the 7th pulse, in which only four slots separate the two pulses, the pulse energy has built up sufficiently prior to the second pulse that communication is possible. In fact, for most pulses, more energy than necessary is retained in the cavity, affording the potential of increased communication efficiency through a combination of (1) modulation of pump power, (2) holding off cavity buildup with the EOM, or (3) reducing average pump power level.

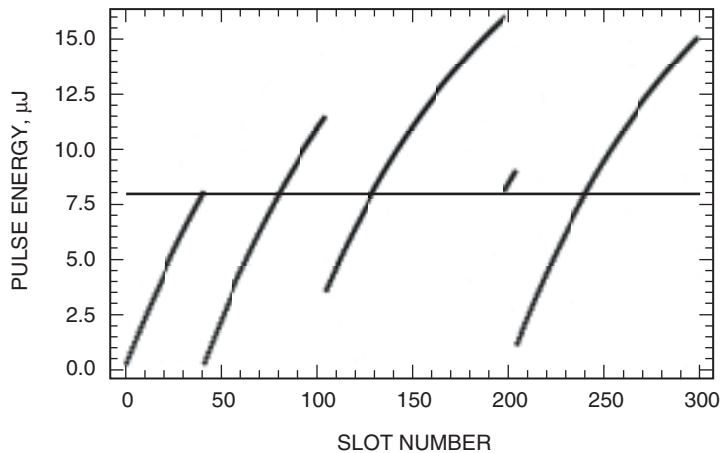


Fig. 8. Overdriving a PPM-encoded cavity-dumped laser generates the possibility for emitting sufficiently energetic pulses at time intervals significantly less than the nominal dead time.

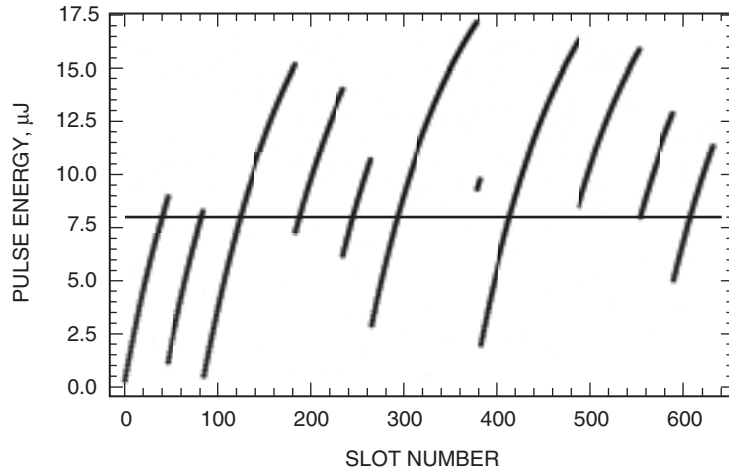


Fig. 9. Pulse energy values for the encoded sequence found in the text. Note the closely spaced pulses 6 and 7, where 8 μJ of energy are emitted in near-sequential slots.

For about 85 percent of a Mars–Earth conjunction cycle, the pulse energy requirement of our point design link is below 3 μJ , which is significantly less stressing than the 8- μJ requirement because of the increased marginal efficiency of the cavity at low power (see Fig. 10). At full pump power and with a 99 percent efficient cavity, the energy buildup occurs within about 15 passes, so a mean pulse-repetition rate of about 320 μs is possible, leading to a PPM word of 5 bits. For this example, several pulses do not meet the 3- μJ requirement, principally because the initial pulse buildup was insufficient. By extending the initial buildup time by a single word length, and retaining all unused pulse energy, the circulating power can be built up sufficiently that all subsequent pulses are sufficient, as shown in Fig. 11 for the same sequence.

IV. Cavity Design

The design of a cavity for optimum optical efficiency is important for the successful development of a high-rate cavity-dumped laser. This is achieved by minimizing the number of surfaces with which the optical wave must interact, making use of extremely high-clarity materials, and adhering to high surface quality and cleanliness standards. In determining the efficiency of a cavity, it is estimated that good commercial laser high-reflectance mirrors are 99.8 percent efficient, and that good antireflection coatings can reduce Fresnel reflections to about 0.2 percent. In addition, typical surface scatter is about 0.2 percent per surface, which can be reduced below 0.1 percent per surface with care. Brewster-angle surfaces can readily achieve transmission losses of less than 0.1 percent for the P polarization. Total internal reflection is virtually lossless, as long as the surface is uncontaminated. Finally, although internal scatter and absorption exist for many materials, they are considered negligible in comparison.

A simple, inexpensive prototype laboratory laser will be developed with (1) an Nd:YAG laser crystal coated for high transmission at 808 nm and high reflectance at 1064 nm on one end, and anti-reflection (AR) coated for 1064 nm on the other end, (2) a 1064-nm high-reflectance (HR) mirror, (3) a 1064-nm polarizing beam splitter, and (4) a rubidium titanyl phosphate (RTP) EOM. This equipment will be set up in the configuration shown in Fig. 12. An existing 30-W fiber-coupled 808-nm (red rays) diode laser source is shown focused into the Nd:YAG laser crystal. The normal cavity oscillation mode (green rays) is shown in an L-configuration because the polarizing beam splitter is more efficient (99.9 percent) in reflection (S-wave) than transmission. After reflecting from the internal diagonal surface of the beam splitter, the S-polarized beam then goes through the EOM, which is nominally in the off condition, and has no effect on beam polarization. Finally, the beam reflects from the HR end mirror and retraces the cavity. When the EOM is switched on, the S-polarized wave experiences an electrically induced birefringence, changing the

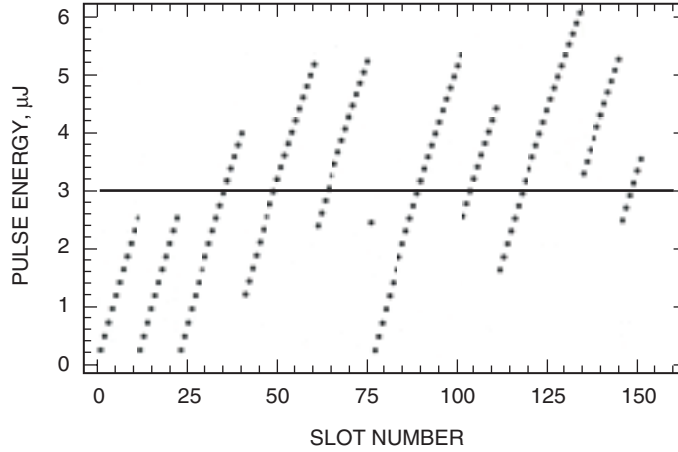


Fig. 10. Rapid pulsing of a dead-time-free cavity-dumped laser operating with a 3- μJ pulse energy requirement. Without initial cavity buildup, some pulses do not meet the threshold requirement.

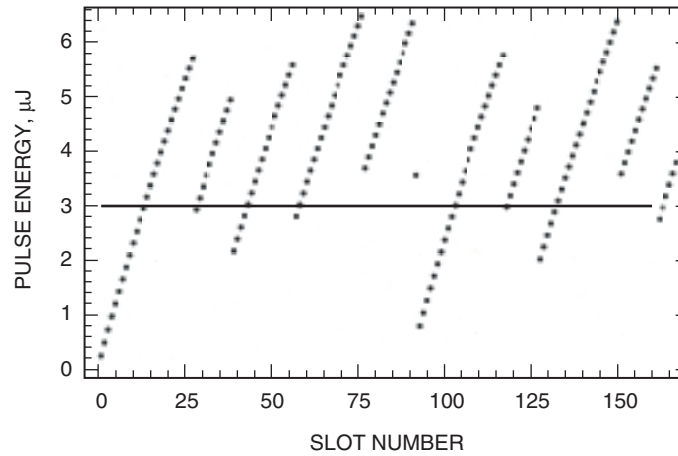


Fig. 11. Initial pulse buildup allows all subsequent pulses to meet the 3- μJ threshold requirement.

linearly polarized beam to elliptical polarization, the ellipticity being dependent on the applied voltage, electro-optic coefficient of the material, and the wavelength of the beam (1064 nm). If the field is strong enough for the particular set of conditions, a quarter wave of retardation can be induced between the ordinary and extraordinary waves of the beam, creating a circular polarization. After reflection from the end mirror, the circularly polarized beam experiences the birefringence of the EOM once again, and is changed back to a linearly polarized beam, but orthogonal to the incident polarization (P-polarized). The polarizing beam splitter transmits P-polarized light, coupling the light out of the cavity.

In this configuration, with off-the-shelf commercial-grade components, a round-trip cavity efficiency of approximately 95 percent is anticipated. Most of this loss (up to 3 percent) comes from the off-the-shelf RTP EOM. The bulk of the remainder is in the excess loss at the pumping surface of the Nd:YAG crystal, assumed to be only 99 percent efficient because of the requirement of high transmission at 808 nm. While the 95 percent efficiency probably is not adequate for meeting the requirements for a space-based cavity-dumped communication laser, it will nevertheless support development and testing of the electronic switching system for efficient driving of the EOM at high rates.

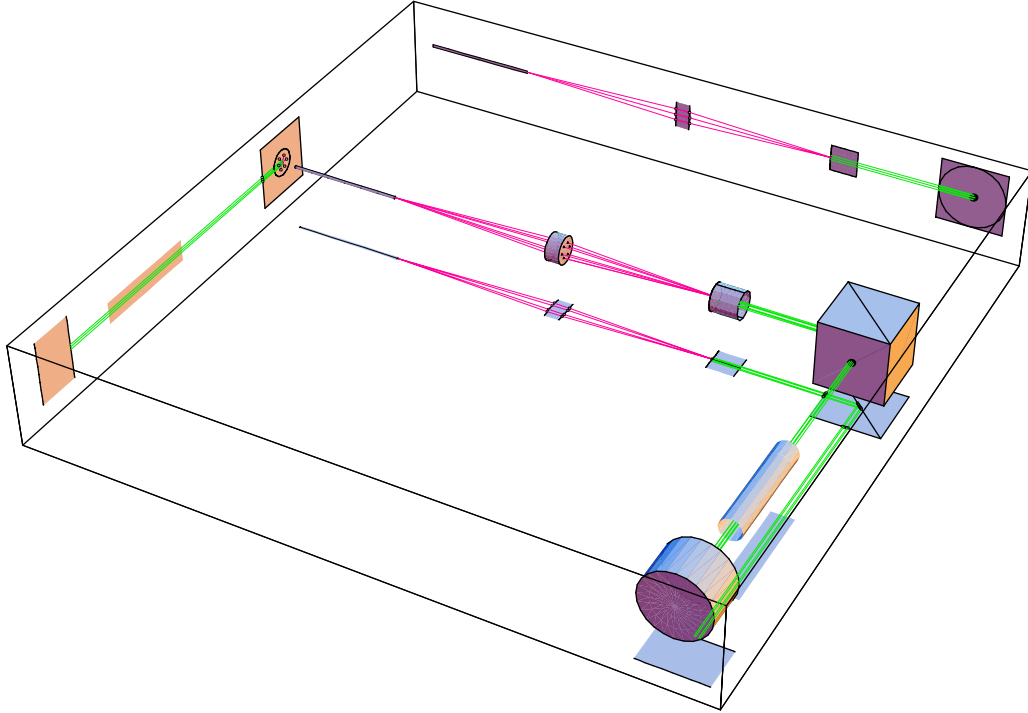


Fig. 12. Optical schematic showing the laboratory design for a high-rate cavity-dumped laser.

The next-phase research laser may use a ring cavity, making use of Brewster surfaces and total internal reflection to the maximum extent. Similar cavities have been developed in recent years in support of ring-down spectroscopy and have achieved total round-trip efficiencies of about 99.95 percent (without the EOM and ring isolator) [18]. A high-efficiency RTP EOM is in design. The ring isolator can be developed using optically clear materials and all Brewster surfaces for high optical efficiency (99.8 percent), resulting in an expected total cavity efficiency approaching 99 percent.

V. Summary

Cavity-dumped lasers have advantages over Q-switched lasers for high-rate PPM communications. At power and efficiency levels envisioned for future space missions, they appear to have the potential for building up and emitting pulses with the energy and pulse width required to reliably perform deep-space communications at a 10- to 100-Mb/s rate. To meet efficiency requirements, a highly efficient laser cavity that is capable of retaining 99 percent of the cavity energy per pass should be developed.

Cavity dumping is sufficiently flexible to support higher rates of communication from shorter distances. By varying the output coupling by adjusting the voltage on the EOM, a controllable amount of energy can be maintained in the intracavity field. This allows the system to emit two separate pulses of adequate communication energy within times shorter than the nominal pulse buildup time. By doing so, the laser dead-time constraint can be reduced or eliminated altogether.

It is expected that these results will be extended by incorporating improved efficiency from hybrid Q-switching/cavity dumping to improve the long-term storage efficiency of the laser energy. Improvements in energy efficiency and bit rate also are expected once coding techniques are applied to the data stream.

References

- [1] T. Tolker-Nielsen and G. Oppenhauser, “In-Orbit Test Result of an Operational Optical Intersatellite Link between ARTEMIS and SPOT4 SILEX,” *Proceedings of the SPIE*, vol. 4635, pp. 1–15, January 2002.
- [2] M. Reyes, Z. Sodnik, P. Lopez, A. Alonso, T. Viera, and G. Oppenhauser, “Preliminary Results of the In-Orbit Test of ARTEMIS with the Optical Ground Station,” *Proceedings of the SPIE*, vol. 4635, pp. 38–49, January 2002.
- [3] J. R. Lesh, L. J. Deutsch, and W. J. Weber, “A Plan for the Development and Demonstration of Optical Communications for Deep Space,” *The Telecommunications and Data Acquisition Progress Report 42-103, July–September 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 97–109, November 15, 1990. http://tmo.jpl.nasa.gov/tmo/progress_report/42-103/103J.PDF
- [4] K. Shaik, D. Wonica, and M. Wilhelm, “Optical Subnet Concepts for the Deep Space Network,” *The Telecommunications and Data Acquisition Progress Report 42-115, July–September 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 153–181, November 15, 1993. http://tmo.jpl.nasa.gov/tmo/progress_report/42-115/115m.pdf
- [5] W. K. Marshall, K. Cowles, and H. Hemmati, “Performance of Efficient Q-Switched Diode-Laser-Pumped Nd:YAG and Ho:YLF Lasers for Space Applications,” *The Telecommunications and Data Acquisition Progress Report 42-95, July–September 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 168–173, November 15, 1988. http://tmo.jpl.nasa.gov/tmo/progress_report/42-95/95P.PDF
- [6] H. Plaessmann, K. S. Yamada, C. E. Rich, and W. M. Grossman, “Subnanosecond Pulse Generation from Diode-Pumped Acousto-Optically Q-Switched Solid-State Lasers,” *Applied Optics*, vol. 32, no. 33, pp. 6616–6619, November 20, 1993.
- [7] H. Plaessmann, S. A. Re, J. J. Alonis, D. L. Vecht, and W. M. Grossman, “Multipass Diode-Pumped Solid-State Optical Amplifier,” *Optics Letters*, vol. 18, no. 17, pp. 1420–1422, September 1, 1993.
- [8] V. P. Gapontsev, V. V. Fomin, I. E. Samartsev, and A. Unt, “25 kW Peak Power, Wide-Tuneable-Repetition-Rate and Pulse Duration Eye-Safe MOPFA Laser,” *Summaries of Papers of the Conference on Lasers and Electro-Optics '96*, pp. 209–211, June 2–7, 1996.
- [9] V. P. Gapontsev, N. S. Platonov, M. Vyatkin, M. Meleshkevitch, D. Spinov, and I. Zaitsev, “3W Saturation Power Polarisation Maintaining 1060 nm Ytterbium Fiber Amplifier,” *Proceedings of the SPIE*, vol. 3615, pp. 264–268, January 1999.
- [10] J. A. Alvarez-Chavez, H. L. Offerhaus, J. Nilsson, P. W. Turner, W. A. Clarkson, and D. J. Richardson, “High-Energy, High-Power Ytterbium-Doped Q-Switched Fiber Laser,” *Optics Letters*, vol. 25, no. 1, pp. 37–39, January 1, 2000.
- [11] G. C. Valley and M. Wright, “Modeling Transient Gain Dynamics in a Cladding-Pumped Yb-Doped Fiber Amplifier Pulsed at Low Repetition Rates,” *Summaries of Papers of the Conference on Lasers and Electro-Optics 2001*, Paper CWA-51, CLEO 2001 Conference, Baltimore, Maryland, May 6–11, 2001.

- [12] W. Koechner, *Solid-State Laser Engineering*, 4th ed., Berlin, Germany: Springer, pp. 452–483, 1995.
- [13] G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed., San Diego, California: Academic Press, 1995.
- [14] E. Kruger, “High-Repetition-Rate Electro-Optic Cavity Dumping,” *Review of Scientific Instrumentation*, vol. 66, no. 2, pp. 961–967, February 1995.
- [15] D. L. Robinson and M. D. Rayman, “Calculations of Laser Cavity Dumping for Optical Communications,” *The Telecommunications and Data Acquisition Progress Report 42-95, July–September 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 174–179, November 15, 1988.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-95/95Q.PDF
- [16] D. L. Robinson, “A Novel Approach to a PPM-Modulated Frequency-Doubled Electro-Optic Cavity-Dumped Nd:YAG Laser,” *The Telecommunications and Data Acquisition Progress Report 42-97, January–March 1989*, Jet Propulsion Laboratory, Pasadena, California, pp. 240–247, May 15, 1989.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-97/97Z.PDF
- [17] G. W. Hollerman and G. S. Mecherle, “Optimization of Pulse Position Modulation Communication when Using a Cavity-Dumped Nd:YAG Laser,” *Proceedings of the SPIE*, vol. 2123, pp. 254–263, January 26–28, 1994.
- [18] R. D. vanZee, J. P. Looney, and J. T. Hodges, “Measuring Pressure with Cavity Ring-Down Spectroscopy,” *Proceedings of the SPIE*, vol. 3535, pp. 46–56, 1998.