Calculations of Laser Cavity Dumping for Optical Communications

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For deep-space pulse-position modulation (PPM) optical communication links using Nd:YAG lasers, two types of laser transmitter modulation techniques are available for efficiently producing laser pulses over a broad range of repetition rates: Q-switching and cavity dumping. The desired modulation scheme is dependent on the required pulse repetition frequency and link parameters. These two techniques are discussed, theoretical and numerical calculations of the internal energy of the laser cavity in cavity dumping are described, and an example of cavity dumping is applied to a link for a proposed experiment package on Cassini.

I. Introduction

A link-analysis approach is a standard aspect of the development and design of a communications system. It is essential to have confidence that the component performances assumed in these link calculations are realizable. Because some of the key components in optical communications are still in the development phase, it is necessary to use theoretical analyses to support the performance assumptions made in the link studies.

One of these key components is the laser transmitter. The laser most likely to be used is a neodymium-doped yttrium aluminum garnet (Nd:YAG) crystal end-pumped by laser diodes. In contrast to flash-lamp pumping, laser diodes can provide pump light at one of the atomic resonant absorption bands of the Nd^{3+} ion to improve pumping efficiency. (It is the rare-Earth ion Nd^{3+} in the Nd:YAG that lases. The YAG is simply the host matrix.) By mode-matching the pump light into the laser cavity, the absorption of pump photons is made to occur exactly where the lasing takes place, and the absorption length is greater than in the common side-pumping geometry. With this architecture, overall electrical-to-optical efficiencies in excess of 10% have been demonstrated [1].

In order to implement deep-space optical communications, the extremely energy-efficient pulse-position modulation (PPM) scheme will be used. This modulation format puts severe demands on the performance of the laser transmitter, and it is very important to verify that the required performance that has been assumed in link calculations is achievable. In this article we report on progress in our understanding of the behavior of a modulated laser used for deep-space communications. Two regimes of modulation, Q-switching and cavity dumping, are discussed, and a study of a laser performing in the latter mode follows. Although this study does not model cavity dumping completely, it does provide valuable insight into the process. We evaluate the buildup of energy prior to the emission of a signal pulse. This is a necessary step to insure that the energy required for deep-space optical communications is available in the laser cavity using realistic system parameters. The cavity-dumping analysis here is applied to an example of an optical communications link from Cassini during its interplanetary cruise. A detailed analysis of Q-switching will be presented in a future report.

II. Modulation Techniques and Applications

Two of the common techniques for achieving high-peak-power pulses from the Nd:YAG lasers are Q-switching and cavity dumping. In Q-switching, the energy is stored in the atomic population inversion by keeping the Q of the cavity too low to support laser oscillation. This is accomplished with the use of an element in the cavity whose loss can be controlled. Atoms are pumped to the upper state, but in the absence of stimulated emission, the upper-state population will be greater than in the equilibrium condition achieved when lasing occurs. When the Q is increased (by reducing the loss), the energy in the atoms is immediately available, and the stimulated-emission rate becomes large. A high-energy pulse then depletes the upper level, and lasing temporarily ceases. If the Q is reduced at that point, the pump energy will again begin accumulating population in the upper state. Q-switching has an upper limit imposed by the finite time required to repump the population inversion and by the cavity-field buildup time [2]. A pulse-repetition frequency (PRF) on the order of 50 kHz is the maximum value that can provide high-peak-power pulses from Q-switched Nd:YAG.

For pulse rates much higher than 50 kHz, the technique of cavity dumping is preferred. Although cavity dumping can be extremely efficient at frequencies of many megahertz, it is less efficient at low pulse-repetition rates. As PRFs increase, the choice between Q-switching and cavity dumping will depend on specific laser design parameters and link requirements. The optimal transition point will be understood after further study. In cavity dumping, instead of storing the energy in atoms, the energy is stored in the photon field of the cavity. The output-coupling strength is varied so that the energy in the cavity is extracted when it is needed. The laser is kept above threshold during the entire process.

Both of these modulation techniques have application to deep-space optical communications. Examples of specific optical links between a planetary spacecraft and Earth-based receivers will illustrate this. We have proposed to include an optical-communications package on Cassini. Second in the series of Mariner Mark II spacecraft, it will be targeted for Saturn orbit and will release a probe into the atmosphere of Titan. Currently, launch is expected in 1996. Although the prime communications system will use radio-frequency technology, there may be an opportunity to include an optical communications experiment package to prove out its technology, increase the data return rate, and perform a number of "light science" experiments which take advantage of the on-board laser, telescope, and other optical components.

One configuration of the Cassini optical package uses a 30-cm telescope for the transmit/receive antenna. A frequency-doubled Nd:YAG laser with an average power of 1 W would serve as the transmitter. Transmitting to a 10-m Earth-based receiver under clear skies [3], this system could return over 115 kb/sec from 9 AU. This includes Saturn being in the field of view of the receiver, and the calculated link margin is 3 dB [4]. To achieve this impressive performance, a PPM alphabet size of M=256 is used, and the width of each slot is 10 nsec. With the use of coding, the bit error rate is 10^{-5}.

Because PPM with M=256 transmits 8 bits per pulse, a data rate of 115 kb/sec requires 14,375 pulses per second. The duty cycle is obviously quite low, the laser being on for a total of only about 144 μsec each second. The dead time between the 256-slot words is 67 μsec. This mode of operation is comfortably in the Q-switch regime. With an average laser power of 1 W, each of the pulses has a peak power of almost 7 kW.

During interplanetary cruise, Cassini may be used to demonstrate much higher data rates. Using 256-ary PPM with 10-nsec slot widths and about 2.6-μsec dead time between words, the optical communications package could return 1.54 Mb/sec from 5 AU (the distance of Jupiter) with a 3-dB margin. This does not assume Jupiter to be in the field of view. To transmit 1.54 Mb/sec with M=256 PPM, the laser is required to emit 192.5 kilopulses per second. To maintain 1 W average power, each pulse requires a peak power of 519 W. Based on our present understanding, maximally efficient performance at this PRF necessitates the use of cavity dumping.

These examples illustrate the importance of both Q-switching and cavity dumping for deep-space optical communications. Detailed understanding of laser performance under both operating conditions is essential. In the following section, we present calculations of a laser using cavity dumping to achieve the higher Cassini data rate from 5 AU.

III. Analysis and Calculations of Cavity Dumping

It is important for us to understand the details of the behavior of a Nd:YAG laser operating in a cavity-dumping mode in order to make accurate predictions of its performance and design an efficient system. Following the work of Chesler and Maydan [5], we can calculate the approximate performance of a Nd:YAG laser on Cassini at 5 AU as discussed above. These calculations describe the population inversion and internal field of the laser during buildup in preparation for emitting an output pulse. This initial approach to modeling cavity dumping does not include frequency doubling or the output pulse generation and its characteristics. But we shall see that it does allow us to determine and verify some important aspects of the laser performance. Chesler and Maydan begin with the rate equations for a continuously pumped laser:

$$\frac{dN}{dt} = R - \Gamma N - \beta F N \tag{1a}$$

and

$$\frac{dF}{dt} = \beta F N - (\epsilon + T) F \tag{1b}$$

In these equations, N is the number of atoms in the upper laser level; F is the number of coherent photons in the cavity; t is time; R is the number of atoms pumped up per second; Γ is the spontaneous-decay rate of the upper laser level; and βFN is the number of atoms per second undergoing stimulated emission. The stimulated emission coefficient β may be expressed as $c\sigma/AL$, where σ is the laser transition cross section, A is the cross-sectional area of the laser beam in the Nd:YAG rod, and L is the optical length of the cavity. $\epsilon \equiv c\Delta/2L$ is the reciprocal of the cavity decay time (not including losses from intentional output coupling), where Δ is the round-trip fractional inherent cavity loss. Similarly, $T \equiv c\alpha/2L$ is the reciprocal of the cavity decay time (including only intentional output coupling), where α is the fractional output coupling. During the buildup phase of the cavity dumping cycle, $\alpha = 0$. In order to extract a pulse, in the ideal case, the value of α would be changed to 1, thus allowing 100% of the stored energy to be emitted in a pulse. In reality some losses will be incurred in this process, but this analysis considers only the internal energy of the laser cavity.

These two equations can be understood by considering the physical processes involved in laser physics. Equation (1a) describes the time dependence of the atomic population inversion. The inversion is increased by atoms being pumped up to the upper laser level by the pump source, and it is diminished by both spontaneous and stimulated emission. The latter effect provides a positive contribution to the photon field in the cavity, and that is reflected in the first term on the right side of Eq. (1b). This equation describes the time dependence of the number of photons in the field of the cavity. The second term in that equation reflects the loss of photons through inherent and intentional losses in the cavity.

For a given cavity design, T will be fixed. It can be shown by maximizing the output power that the optimum cw values for N and F, given fixed T, are $N_0 = \epsilon\phi^{1/2}/\beta$ and $F_0 = \Gamma(\phi^{1/2} - 1)/\beta$. The parameter ϕ is defined to be $R\beta/\Gamma\epsilon$, which is the ratio of the pumping rate to the threshold pumping rate. Of course, in storing and dumping the energy in the cavity, the interest is in the deviations from the cw performance. Thus, we introduce n and f to describe these deviations, and we have $N = N_0 + nN_0$ and $F = F_0 + fF_0$.

Chesler and Maydan make a number of reasonable approximations to arrive at expressions for these deviations. One of the key assumptions is that the duration of an output pulse is short compared to the buildup time between pulses. In our example, this is seen to be an excellent assumption, since the pulse duration of 10 nsec is less than 0.4% of the minimum time between pulses. The approximate solutions are found to be

$$n = \frac{\gamma\Gamma}{\epsilon}\left(\frac{1}{\gamma} - \frac{1}{2} + \frac{s}{\tau} - \frac{e^{\gamma s/\tau}}{e^{\gamma} - 1}\right)$$

and

$$f = \frac{\gamma e^{\gamma s/\tau}}{e^{\gamma} - 1} - 1$$

where $s \equiv t\epsilon$, or the time in units of the cavity decay time; τ/ϵ is the time between pulses, during which the field intensity accumulates; and $\gamma \equiv \tau(\phi^{1/2} - 1)$.

With these expressions, we can calculate the evolution of the upper-state population and the optical field for cavity dumping in the regime of validity for these solutions. Because the development began with rate equations, the results do not apply when the number of coherent photons in the cavity is reduced to the order of one. At this level, the statistics of spontaneous emission control the buildup of the field, and the rate-equation approach is not appropriate.

Our interest now is in finding N/N_0 and F/F_0. We consider the case of a cavity with inherent loss $\Delta = 0.03$ and a length $L = 20$ cm. These combine to give a cavity decay time of $\epsilon = 44$ nsec. (Recall that ϵ does not include intentional output coupling. By increasing the output coupling, α, when it is time to emit the energy, 10-nsec pulses can be achieved. The technique used in this report to examine cavity dumping does not allow us to study the output pulse.) To calculate the parameter β, we use $\sigma \approx 5.75 \times 10^{-23}$ m^2 for Nd:YAG [6], and $A = 3.14 \times 10^{-6}$ m^2. Thus we find $\beta = 2.74 \times 10^{-8}$ Hz. The fluorescence lifetime of the upper state in the Nd:YAG laser line is 230 μsec, so $\Gamma = 4350$ Hz.

Using the output coupling which comes from the optimum cw values for N and F as outlined above, we can calculate a pumping rate which guarantees an average power of 1.0 W. This turns out to correspond to a pumping rate above threshold of $\phi = 4.9$. We know this is achievable, since this value of ϕ is less than that previously demonstrated for diode pumping of Nd:YAG lasers [7].

With these values, we determine n and f and thus N/N_0 and F/F_0 as functions of time. The results of these calculations are shown in Figs. 1 and 2.

At time 0 in both figures, the system is beginning just after a pulse has been produced. The pump energy is building up population in the upper level of the laser line and contributing to the field energy. When the field energy passes the cw optimum value of $F = F_0$ (Fig. 2), the rate of stimulated emission becomes large enough to begin reducing the population in the upper state. The upper-state population (N) begins to decline (Fig. 1), and it never varies significantly from the cw value. When the inversion decreases, energy is transferred into the optical field by stimulated emission until the designated time to dump the cavity. When it is time to produce a pulse, the output coupling (α) is changed, and the internal-field energy drops as it is emitted in the narrow pulse. The greatly reduced internal field causes a reduction in the stimulated-emission rate, so the population inversion begins to increase again and the entire cycle starts over.

From our calculations of the laser performance, we find that the cavity accumulates 5.17 μJ at the maximum. It is at that point that the pulse is produced by changing the output coupling. Although the approach used here does not address the dynamics of the output signal, if we assume that all of this available energy is emitted in a 10-nsec pulse, it produces a peak power of 517 W. This is within less than 1% of the values derived from the Cassini link calculation and is achieved with the laser component values we have used.

IV. Conclusions

Within the limitations of this initial approach to understanding cavity dumping, we can see that the performance assumed for the laser transmitter in the optical link calculations is justified. Realistic laser parameters with an achievable pumping rate will lead to production of the stored energy needed for the Cassini link from Jupiter.

A detailed understanding of the laser operation during cavity dumping is crucial to the design of a laser capable of providing the signals needed for the pulse-position modulation to be used in our optical-communications system. The approximate solutions used here provide a starting point for that understanding, but more needs to be done. One of the assumptions of the derivation is that the dumping is periodic. Of course, since the transmitted information is contained in the time during which the pulse is transmitted, varying times between pulses must be considered. This would allow the field energy and population-inversion energy to continue to evolve for different lengths of time between signals. A more detailed analysis of this factor would reveal exactly how it affects the uniformity of the output pulses. In addition, a study of pulsed pumping would be necessary in order to insure that the stored energy is maximum just before the output coupling is raised to release that energy as an output signal. Further, to achieve still higher data rates, operation in a regime where the time between pulses is not large compared to the pulse width is required, as has been assumed here. For Cassini at Mars range, data transmission of 20 Mb/sec is planned. To achieve that rate with 10-nsec pulses will require a dead time of only 40 nsec and an alphabet size of 16. An analysis of the performance of the laser transmitter under these conditions requires use of the exact solution. Such an analysis should include the actual extraction of the pulse to reveal its characteristics in detail. A careful comparison of Q-switching and cavity dumping in the PRF range where they overlap will allow the determination of the preferred scheme of modulation under different link scenarios.

References

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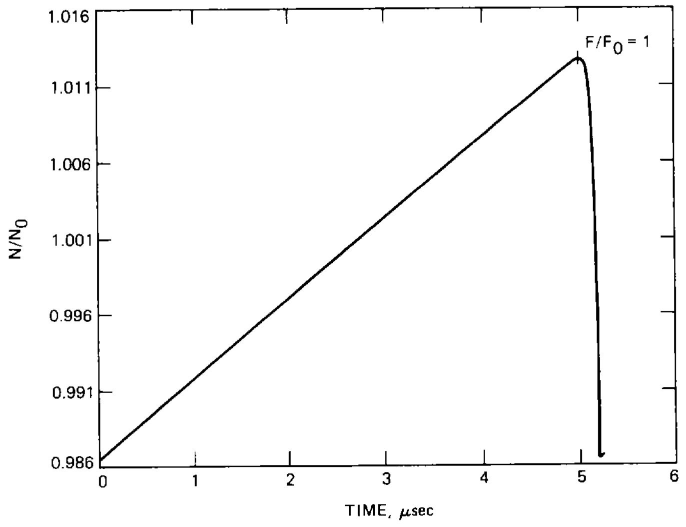

Fig. 1. Normalized population inversion as a function of time.

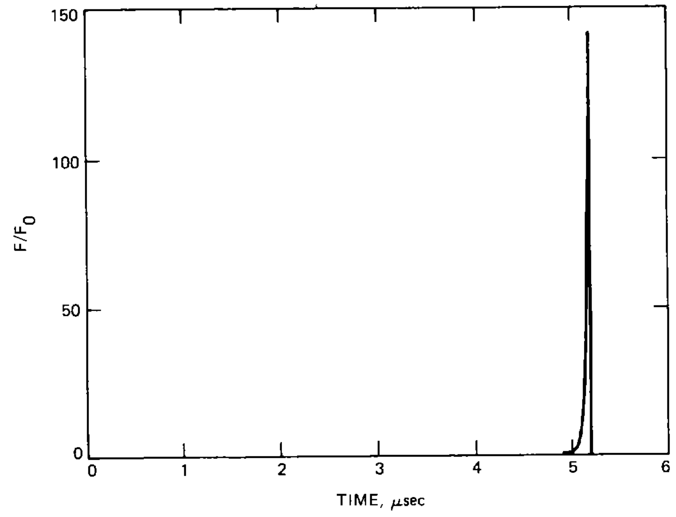

Fig. 2. Normalized field as a function of time.