MICROWAVE-MODULATED TRANSMITTER DESIGN FOR HYBRID LIDAR-RADAR

L. Mullen*, A. Vieira*, P.R. Herczfeld*, V.M. Contarino#

*** Center for Microwave and Lightwave Technology, Drexel University, Philadelphia, PA 19104**
 # Naval Air Warfare Center, Warminster, PA 18974

ABSTRACT

The application of well-established, coherent RADAR technology to aerial light detecting and ranging (LIDAR) systems has reduced incoherent backscatter clutter by 17 dB in laboratory experiments and computer simulations. The full-scale experimental realization of this hybrid LIDAR-RADAR system is hampered by the unavailability of a stable modulation source capable of providing high peak powers to overcome the large dynamic range required for the LIDAR backscatter measurement. Two methods being investigated for the microwave-modulation of a transmitted optical pulse to be utilized in the actual LIDAR environment are detailed.

INTRODUCTION

RADAR is the principal tool for remote sensing of the earth and atmosphere because of its sensitivity, resolution, and accuracy - a result of sophisticated, coherent detection techniques. RADAR, however, cannot be used directly for the detection of underwater objects since microwaves do not penetrate water. Currently, shipboard SONAR systems are employed for the detection and ranging of objects submerged in the sea. However, the use of aerial LIDAR systems is gaining popularity due to their increased speed and area coverage [1]. The main disadvantage of LIDAR is that it lacks coherent detection schemes, which limits system sensitivity and underwater target contrast.

Past publications reported on a new concept, the merging of RADAR and LIDAR technologies in the creation of a hybrid LIDAR-RADAR detection scheme. To test this new technique in a laboratory environment, a simple, inexpensive ocean mass simulator (OMS) was developed [2]. The use of this OMS to evaluate the coherency of the microwave signal as it propagates in the water medium was reported in [3]. The computer simulation and experimental setup based on the OMS and utilizing the hybrid LIDAR-RADAR detection scheme were described by Mullen *et al.* [4]. The theoretical and experimental analysis of a hybrid LIDAR-RADAR system revealed a 17 dB reduction of the backscatter clutter, with a corresponding enhancement of underwater target contrast. The accomplishments of the laboratory experiments established the significant potential of this new technique and led to the desire to develop a system capable of integration into an existing LIDAR system [5]. The main experimental restriction in the full-scale realization lies in our inability to generate a stable and efficient microwave modulation of the transmitted optical pulse.

The challenge in developing a modulated pulse LIDAR system lies in the dynamic range of the backscatter measurement. The attenuation experienced by the blue-green optical signal as it traverses the water medium varies from .05 dB/m in clear water to 0.25 dB/m in dirtier water [6]. Therefore, for a 100 m water depth, the optical signal will attenuate by 10 - 50 dB, which is in addition to the 40 dB reflection loss. The laser therefore, must transmit high peak power to overcome the 50 - 90 dB system losses. Thus, the typical LIDAR transmitter is a Q-switched, frequency doubled Nd:YAG laser with peak output powers reaching the tens of megawatts.

For the hybrid scheme we must find a method of modulating this very high power, blue-green laser pulse at microwave frequencies. In general, a narrow bandwidth microwave amplitude modulation format is desired. Although a limited number of bulk external modulators capable of handling high optical power inputs at microwave modulation frequencies are commercially available, their performance is inadequate. Specifically, the state-of-the-art 3 GHz bulk modulator which was used in our laboratory experiments yielded a modulation depth of less than one percent. The second approach used in the earlier experimentation [4] exploited the longitudinal mode-beating of the multimode Nd:YAG laser. Although this self-modulation of the laser produced microwave-modulated, blue-green pulses at reasonably high optical power levels, frequency stability and pulse to pulse repeatability is a problem.

The two alternate methods for producing microwave modulation of a blue-green optical pulse are based on improvements in these existing techniques. The first modulation scheme consists of placing the existing external bulk phase modulator in a Fabry-Perot cavity. The second method is based on improving the stability of the self-modulation of the Nd:YAG through mode-locking techniques.

BULK FABRY-PEROT MODULATOR

The basic notion is to place a bulk E-O modulator, which has very low modulation index, but can support high optical power densities, in a Fabry-Perot cavity. The Fabry-Perot configuration allows for multiple passes through the modulator, which is expected to enhance the modulation index. The normalized transfer function for a lossless Fabry-Perot modulator is [7]

$$\frac{I_t}{I_o} = \frac{1}{1 + N \sin^2(\delta/2)} \qquad (1)$$

where $N=4R/(1-R)^2$= cavity factor, R is the mirror reflectance, and δ is the phase difference.

Amplitude modulation is achieved by inducing a phase change in the optical beam as a function of the modulating signal when the modulator is biased to half-transmission point [8]. The phase change is [9]:

$$\Delta\delta = \frac{\pi r n^3}{\lambda_o} \frac{L}{d} V \qquad (2)$$

where r is the E-O coefficient, n is the optical refractive index, L and d are the length and thickness of the modulator, λ_0 is the wavelength, and V is the applied voltage.

The concept was tested by placing a MgO-$LiNbO_3$ E-O modulator in a Fabry-Perot cavity formed by two 90% reflecting mirrors. The mirrors were separated by a distance of 22.4 cm, that could be fine tuned by a piezo-electric controlled positioner, to produce a resonant condition in the optical and in the microwave domain (at 3 GHz), simultaneously. The

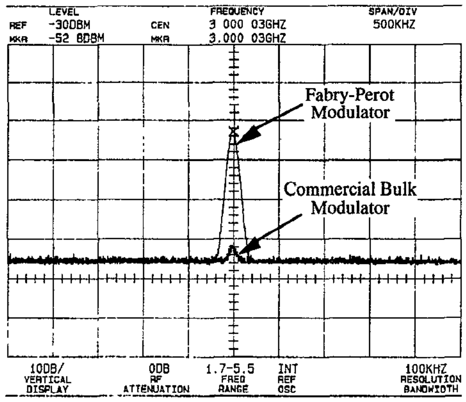

Fig. 1. Spectrum of the 3 GHz modulation produced by both the stand-alone bulk modulator (bottom signal) and the Fabry-Perot modulator (top signal).

finesse of the cavity, with the modulator, was measured as F=9.06. First, the modulation characteristics of the stand-alone commercial E-O phase modulator in an amplitude modulation mode and with a continuous wave optical input were determined. The amplitude of the 3 GHz modulation was detected by a spectrum analyzer, and displayed in Fig. 1. The -83 dBm signal, shown in Fig. 1, corresponds to a modulation depth of 0.18% at 3 GHz with an applied microwave power of 15 dBm. Next, the same modulator with identical microwave input, but now in the Fabry-Perot cavity, registered -53 dBm microwave power at the spectrum analyzer, which corresponds to a modulation index of 4%. Increasing the microwave input power by 20 dB, the maximum tolerated by the device, the modulation index in the stand-alone device is increased to 1.8%, and to 40% in the Fabry-Perot arrangement. The 15 dB increase in the modulation index proved the viability of the Fabry-Perot approach, but the excessive cavity length is impractical for pulsed operation. These results were applied to the design of a compact, efficient modulator for pulsed operation at 532 nm.

The compact modulator was conceived to have dielectric mirrors deposited directly on the opposite faces of the MgO-LiNbO3 crystal to form the optical cavity, as shown in Fig. 2. Electrodes, for the microwave input, are applied to the transverse faces of the crystal. The trade-off between the electrooptic effect and the transit time for different mirror reflectivities was analyzed. For 90% reflective mirrors the optimal

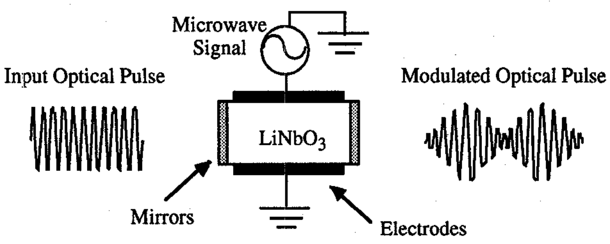

Fig. 2. Fabry-Perot electrooptic modulator.

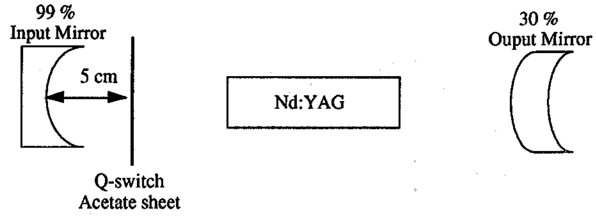

Fig. 4. Resonator configuration using saturable dye to Q-switch and mode-lock the Nd:YAG laser.

crystal length was determined to be 1mm. With this configuration a 50% modulation index and a bandwidth in excess of 4GHz is anticipated.

MODE LOCKING OF A ND:YAG LASER

In past experiments, we were successful in producing high-power, microwave-modulation of the laser pulse from the mode-beating effects of a Q-switched Nd:YAG laser. Mode-selective elements (such as a pockel cell Q-switch and polarizer) within the laser cavity produced a 3 GHz amplitude modulation of the 15 ns optical signal at the detector as shown in Fig. 3. However, the frequency of modulation was inconsistent from pulse to pulse because of the large number of modes supported by the laser cavity. In addition, the lack of a controlled phase relationship among the oscillating modes caused a variation in the modulation depth of the output pulse. Therefore, to use this modulation scheme, further stabilization is required.

The current setup shown in Fig. 4 consists of a standard Nd:YAG laser oscillator with mirrors placed 70 cm apart. An absorbing saturable dye sheet is placed 5 cm from the input mirror, creating a low-Q subcavity which resonates at the desired 3 GHz frequency. This arrangement produces several different effects. First, the saturable absorber generates 45 ns Q-switched laser pulses. Second, the saturable absorber, which has a relaxation time of 300 ps (3 GHz), also produces 2 ns mode locked pulses separated by the main cavity round-trip time of 5 ns. Within the 2 ns mode locked pulses, a 3 GHz modulation is produced by the subcavity. The analysis of the system is very complicated because the saturable absorber is a nonlinear element, whose transmission characteristics are determined by the incident photon field which varies during the pulse build-up time. This in turn appears as a time dependent boundary condition for the waves within the subcavity.

All the essential features of this complex system are displayed in Fig. 5. The 2 ns mode-locked pulses are contained within the envelope of the 45 ns Q-switched pulse. The insert in Fig. 5 is the streak camera output of the mode-locked pulse, which illustrates the superim-

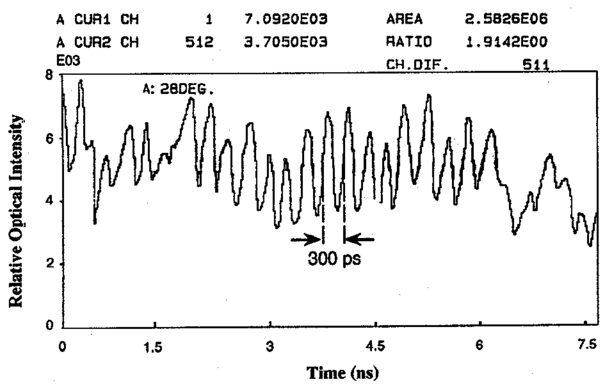

Fig. 3. Streak camera picture of modulation produced by mode-beating effects in a Q-switched, frequency doubled Nd:YAG laser.

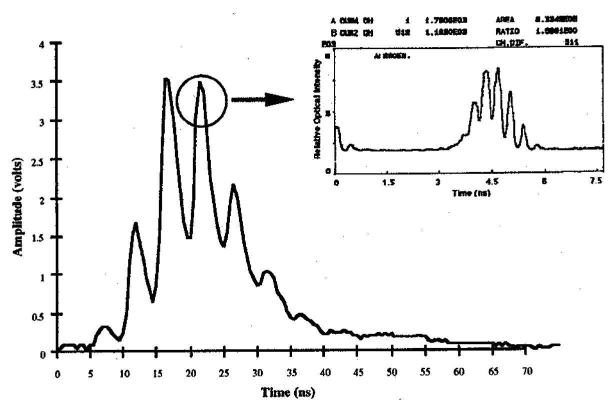

Fig. 5. Q-switched and mode-locked pulse formed by inserting saturable absorber 5 cm from the input mirror of a Nd:YAG laser.

posed 3 GHz modulation. We found experimentally that the microwave modulation frequency changed proportionally with the length of the subcavity, as expected. In addition, the output amplitude fluctuations common in passively mode-locked lasers were evident [10].

The 3 GHz modulation, shown in Fig. 5, is a combination of two effects. First, we have small amplitude modulation initiated by the subcavity and enhanced by the laser. In addition, we still have the mode-beating effects at the detector. Since the laser modulation frequency is controlled by the position of the dye sheet, the frequency stability of the modulation is enhanced. In addition, the modulation produced by mode-beating effects is improved since the modes are phase locked and the spectral content is narrowed by the presence of the saturable absorber. Mode-locking also results in an output with higher peak powers than that achieved with the uncoupled laser resonator. Thus, we have succeeded in constructing a microwave-modulated transmitter with improved frequency stability, simplified cavity configuration, and higher peak powers.

CONCLUSIONS

The success of the full-scale realization of the hybrid LIDAR-RADAR detection scheme lies in the ability to modulate efficiently a high-power, blue-green optical pulse at microwave frequencies. Since the typical laser configuration used in present LIDAR systems is the Q-switched Nd:YAG laser, modulation schemes developed for this application must adapt to this specific laser system. Past attempts at both external modulation through use of a commercially-available bulk modulator and internal modulation using mode-beating effects produced insufficient and unstable modulation of the laser pulse. Therefore, we have developed two new modulation techniques with better performance. The external Fabry-Perot cavity containing a bulk modulator has produced a 15dB improvement in modulation depth over results obtained with the modulator alone. In addition, the amplitude modulation due to mode-beating effects of the Nd:YAG laser was stabilized through use of a saturable dye to both Q-switch and mode-lock the laser. Future plans include designing and manufacturing a compact external Fabry-Perot modulator and improving the pulse and modulation characteristics of the self-modulated Nd:YAG laser.

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