Design and simulation of a simple laser rangefinder using a semiconductor optical amplifier-detector

Arthur James Lowery and Malin Premaratne
Department of Electrical and Computer Systems Engineering
Monash University, Clayton, Victoria 3800, Australia
arthur.lowery@eng.monash.edu.au, malin@eng.monash.edu.au
http://www.ecse.monash.edu.au

Abstract: Using numerical simulations, we show that cross-gain modulation between pairs of counter-propagating pulses within a semiconductor optical amplifier can be used to detect the range and reflectivity of a target, forming a compact time-of-flight laser ranger. The range is deduced from multiple contacts along the SOA. The SOA also provides gain to the optical pulses reflected off the target. A single external component is required to provide pulses into back of the SOA, with the front of the SOA being directly coupled to the target.

©2005 Optical Society of America

OCIS codes: (130.6010) Sensors; (120.0120) Instrumentation, Measurement, Metrology; (250.5980) Semiconductor Optical Amplifiers.

References and links
1. Introduction

Distance measurement using lasers is well developed and common techniques include triangulation, pulse time-of-flight, RF-modulation phase-shift measurement and optical-frequency modulated self-heterodyne systems [1]. Time-of-flight systems offer fast data acquisition [2], but their accuracy is limited by the pulse width [3] and the bandwidth of the receivers [4]. The system usually comprises two photo-receivers, to monitor the transmitted and received pulses. The delay between the transmitted and received pulses is proportional to distance. Recent advances using custom-designed time-to-digital converters [4] give accuracies of better than 0.4 mm after averaging of $10^4$ 10-ns pulses over 1 second. As an alternative technique and to provide compact sensing heads, several groups have utilized direct reflection back into a transmitting laser in order to perturb the operating characteristics of the laser, such as its output power [5, 6, 7]. The laser’s output power will fluctuate with changes in distance, angle and velocity of the target [5]. Techniques that detect mode-hops of a frequency-modulated laser [6] give accuracies of 5 mm over a 5 ms integration time.

In this paper, we develop a time-of-flight laser rangefinder design with a compact sensing head which functions as a power amplifier, a preamplifier and a fast delay to voltage converter. The sensing head is a semiconductor optical amplifier (SOA) chip, which is simply a laser diode with anti-reflection coated facets. However, unlike the designs of [5, 6, 7], our ranger design uses short optical pulses, so the reflections into the chip are compared to the transmitted signal in time, rather than in phase. The output voltage is derived from multiple contacts along the SOA, and gives a precise indication of the time delay between the transmitted and received pulses without the need for high-speed electronics, as required in [4].

2. Design

The design comprises a short optical pulse source (such as an integrated mode-locked laser) and a semiconductor optical amplifier (SOA) as the sensing head, as shown in Figure 1. The SOA provides the controllable gain for the transmitter, controllable gain for the receiver, and electrical signals from which the relative times and amplitudes of the transmitted and reflected pulses can be deduced. Because these multiple functions are provided by a single device, no beamsplitters or optical couplers are required, considerably simplifying the optics. Also, because the SOA detects the relative timing of the transmitted and received pulses and is the last optical device in the chain, the ranging is tolerant to mechanical vibration. Multiple SOAs can be integrated onto a chip (or bar) and fed with a single pulse source, allowing multi-point near-field ranging, or a steer-able array with appropriate optics.
3. Theory of operation

We previously presented a 3-contact SOA device that was capable of comparing the relative timing of two counter-propagating pulse trains [8], fed into the ends of the SOA. The timing was derived from the difference in voltages on the end contacts of the SOA. This design was a simplification on the design of Awad et al. [9] who used photodiodes to detect the output powers at each end of a single-contact SOA. A simple explanation for the operation of our device is as follows [8]. The contacts are connected to constant current sources. We assume that the carrier lifetime is far longer than the pulse width, the transit time of pulses through the SOA and the delay between the pulse trains. Consider a single low-power pulse incident on the left-hand facet of an SOA. This pulse will grow exponentially as it propagates along the SOA, from left to right (“forwards”). At the right facet of the SOA, the pulse will have grown to sufficient power that stimulated recombination becomes significant, reducing the carrier density and gain under the right-most contact. If a pulse is then input to the right facet of the SOA, to travel backwards along the SOA, it will experience this reduced gain and not grow strongly as it propagates towards the left-most contact. Therefore, the carrier density under the left contact will not be reduced as much as the carrier density under the right-most contact was. This imbalance in carrier densities will cause a differential voltage across the end contacts. In the absence of pulses within the SOA, the carrier density relaxes towards a steady-state, causing the differential contact voltage to be a function of time delay. In [8] we showed that a middle contact could be used to improve sensitivity by providing gain.

Although the original application for the device in [8] was to form part of a clock-recovery circuit for high-speed data [10], using numerical simulations we investigated whether the right-traveling pulse exiting the right-facet could be reflected back into the right-facet, to become a suitable left-traveling pulse. Thus the SOA would detect the delay between the reflection point and the SOA itself. One concern was the magnitude of reflectivity that would be required to match pulse energies impinging on the facets. We discovered that a small reflectivity (-30 dB) was sufficient, provided the SOA gave sufficient gain between its inputs and outputs. This meant reducing the magnitude of the input pulses at the left-facet, to reduce the saturation of the SOA’s gain (though some saturation is required for the device to work as a delay detector). Thus the device is suitable for short-range applications such as surface monitoring, though other applications requiring ranging to a reflection point (such as fiber sensors) could use this technique.

![Diagram of powers throughout system using a 3-contact SOA.](image)

The reason for the good reflection sensitivity of the device is that the SOA can provide substantial gain along its length (>30 dB). As shown in Figure 2, this gain is used twice: once to amplify right-traveling pulses that become the ‘transmitted’ pulses and once to amplify the received pulses that have been reflected from the target. The key to successful operation is to obtain equal input powers just inside the facets, \( P_1 = P_2 \). This will ensure equal pulse energies...
when the pulses reach the opposite ends of the SOA in the case when the inputs pulses arrive at the same time. By examining Figure 2, this condition can be met if \( g = 2l + 2f + t \). Thus the total round-trip loss to the target should equal the single-pass gain of the SOA. This condition requires a reasonably high gain, \( g \), along the SOA, and the ability to tailor the SOA’s gain to the round-trip loss to the target. A high-gain can be obtained using a center contact operated at a high bias [8].

4. Simulation

Previously, we simulated a multi-contact SOA delay discriminator to test its performance compared with the design of Awad et al. [8]. This paper extends that simulation to a range-finder. The SOA’s parameters are as in [10]. Figure 3 shows a simplified simulation schematic from VPIcomponentMaker™ Active Photonics, for a 3-contact SOA. This simulator is based on the work of Lowery [10, 11] and uses a time-domain model of the SOA comprising of a number of interconnected model sections, with each section representing a longitudinal slice of the SOA. The interconnections represent the propagation delays of the forwards and backwards-traveling optical fields. Each section contains models for gain, spontaneous emission, carrier-dependent index and loss. Each section also contains a rate equation for carrier density, which is fed by the injection current, but depleted by spontaneous recombination and stimulated recombination calculated from the square of the sum of the forwards and backwards-traveling optical fields. The propagation delays between sections and between external components means that systems can be simulated simply by interconnecting discrete models of components, and so this methods is ideal for simulating systems including bidirectional propagation. Also, the interconnections model real propagation delays exactly, so the dynamics of pulse amplification within SOAs are included into the models.

The pulse rate is 10 Gpulses/s with a width of 12.5 ps and a peak input power to the SOA of 40 µW. This compares with 1 mW in our previous simulations [8], allowing considerable attenuation between the mode-locked laser and the SOA. The target reflectance and the losses and delays in the optical paths to and from the target are represented by a single variable delay and an optical attenuator. Each SOA contact was 126-µm long and driven with a current of 40-mA. The carrier densities under each contact were converted to voltages using a heterojunction model with an ideality factor of 2 and a temperature of 300 K. The simulations were operated at a sampling rate of 2.56 THz, giving a time resolution of better than 400 ps. The simulations were run for sufficiently long for all outputs to reach a steady state.

Figure 4 is the result of sweeping the round-trip delay over a range of 100 ps, for seven different levels of reflectivity. It shows that the sensitivity (slope of the curves) is invariant with reflectivity, but an offset occurs that is proportional to the reflectivity in dB. The sensitivity is approximately 20 mV/ns which translates to 1.33 mV/cm for a round trip at the speed of light. As is, the raw signal would not be able to distinguish between a change in reflectivity and a change in delay. However, several techniques could be used to separate the effect of changing reflectivity from the delay measurement:
1. Sweep the pulse rate of the master oscillator, so that the delay response is swept over an entire period
2. Detect the reflected power with a beamsplitter and a low-frequency photodiode
3. Detect the reflected power from a combination of the contact voltages.

These methods would then require some simple numerical calculations to calibrate the system.

5. Accuracy

The accuracy of the system is governed by optical and electrical noise. To investigate the effect of amplified spontaneous emission within the SOA, ASE was added to the SOA model over a 20-nm equivalent bandwidth. The result was a Gaussian distribution of differential contact voltage. Averaging the contact voltage over 32 pulses (3.2 ns) gave a standard deviation of 74 µV (calculated over 100 runs of 32 pulses), corresponding to a distance accuracy of 0.56 mm rms. This accuracy can be considerably improved by averaging. For example, averaging over 32 µs would increase the accuracy to 5.6 µm rms, while maintaining a system bandwidth of 16 kHz. This compares very favorably with Reference 4.

6. Effect of facet reflectivity

The above simulations assumed that the facets of the SOA were perfectly anti-reflection coated. In practice, reflectivities below $3 \times 10^{-5}$ can be obtained using a combination of angled facets and antireflection coatings [12]. The effective facet reflectivity can be further reduced by introducing lossy regions behind the facets (by partially removing the contact, for example); however, this will reduce the sensitivity of the system. One solution is to only use a single lossy region behind the left-hand facet, and compensate for this by using the high-power pulse from the mode-locked laser. A lossy region is not used behind the right-hand facet as it would decrease both the transmitted and received powers, so would diminish the allowable round-trip loss to the target substantially.

Figure 6 shows the effect of the residual reflectivity of the right-hand facet on the linearity and sensitivity of the ranger. As expected, facet reflectivities in the order of the reflectivity of the external target ($10^{-3}$) and round-trip path will severely compromise performance, as a parasitic pulse reflected from the facet will saturate the amplifier’s gain before the external pulse returns. A facet reflectivity of $10^{-5}$ slightly perturbs the linearity but maintains the sensitivity of the ranger.
7. Subsidiary issues

7.1 Polarization sensitivity of gain

Most SOA designs have some degree of polarization dependence of gain. This could be overcome by using circularly-polarized input pulses, so that the gain received by pulses traveling in both directions is averaged over both linear polarizations.

7.2 Resolving between multiple free spectral ranges

The response of the ranger exhibits periodicity governed by the pulse repetition rate. One method to resolve the range beyond one period would be to use a swept pulse repetition rate, and compute the absolute range form multiple measurements.

7.3 Dynamic range of optical injection

The gain of the SOA allows relatively-weak reflected pulses to be detected without external amplification. However, preliminary investigations using the simulator have shown that the pulse must be significantly stronger than the amplified spontaneous emission (ASE) within the SOA; otherwise the sensitivity of the ranger will be reduced because the gain will be saturated by the ASE. On the other hand, strong pulses will heavily saturate the gain of the SOA as they enter the SOA, rather than only as they exit the SOA as desired. Thus, the differential saturation along the SOA, hence the sensitivity, will be reduced.

8. Conclusions

Our simulations show that a compact and accurate time-of-flight laser ranger can be made using a semiconductor optical amplifier (SOA) as a delay discriminator integrated into the sensing head. Cross-gain modulation between pairs of counter-propagating pulses within the SOA is used to detect the range and reflectivity of a target. The SOA also provides gain to the optical pulses reflected off the target. A single external component provides pulses into the SOA’s rear facet, with the front of the SOA directly coupled to the target. The design has excellent linearity and good sensitivity without the need for high-speed receiver electronics.

Acknowledgments

We should like to thank VPIphotonics (www.vpiphotonics.com) for the use of their simulator VPlcomponentMaker™Active Photonics for the simulations in this paper.