WIDE-BAND SEMICONDUCTOR LASERS AND OPTICAL MODULATORS FOR COMMUNICATIONS

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ABSTRACT

The emergence of wide-band semiconductor lasers and optical modulators has opened up exciting new possibilities in the lightwave transmission of microwave analog signals and multi-gigabit per second digital data. This paper reviews recent progress in wide-band semiconductor lasers and optical modulators. Opto-electronic charactistics, bandwidth limitations, and microwave circuit considerations are described.

1. INTRODUCTION

Wide-band opto-electronic devices such as semiconductor lasers and optical modulators find application in a range of systems that combine optical and microwave technology. Microwave optical analog links and multigigabit-per-second digital systems are two notable examples. Other applications of wide-band optical components include high-speed signal processing, and the optical control of microwave devices and circuits. A key to the successful implementation of microwave optical systems is the ability to impress a microwave intensity modulation signal on an optical carrier, using either a directly modulated light source or a CW light source with an external modulator. This paper reviews recent progress in wide-band semiconductor lasers and optical modulators. The operating priciples of lasers, electro-optic modulators, and electro-absorption modulators will be described. Based on the physics of operation of each device, the modulation characteristics, optical loss, and intrinsic bandwidth of lasers and modulators will be compared. Opto-electronic models will be presented which include device-circuit interactions. Using these models, limitations on device performance will be explored.

2. SEMICONDUCTOR LASERS

The semiconductor laser is the prefered optical source for high-speed lightwave systems. It provides adequate output power for most applications and can be directly modulated at microwave frequencies by superimposing an ac signal on the dc drive current [1]. The direct modulation bandwidth of a semiconductor laser is limited by a number of device-dependent effects [2] but with careful design, modulation bandwidths in excess of 18 GHz can be achieved [3,4]. The chief advantage of the direct modulation approach is its simplicity. However, undesired effects such as frequency chirp [5] and intermodulation distortion [6] may limit system performance. In addition, intensity noise introduced by the laser [7] may degrade the system signal-to-noise ratio.

The capabilities of directly modulated lasers have been illustrated in many experiments. For example, directly modulated semiconductor lasers have been used in digital lightwave transmission experiments operating at bit rates up to 10 Gbit/s [8]. Analog systems using subcarrier modulation techniques [9] have been demonstrated with as many as 60 FM video channels transmitted simultaneously over 18 km of fiber [10], and microwave oscillators at frequencies above 35 GHz have been injection locked with directly modulated semiconductor lasers [11].

The semiconductor laser is a low impedance ($\sim 5\ \Omega$) current-driven device. When fed from a conventional 50-Ω source it will retain its wide intrinsic modulation bandwidth, but most of the incident power will be reflected. In narrow band applications it is possible to impedance match a laser to a 50-Ω source [12], but in broad-band applications such as high bit-rate digital systems, matching becomes a problem.

3. OPTICAL MODULATORS

An alternative to the directly modulated laser is a CW light source (such as an unmodulated semiconductor laser) cascaded with an external optical modulator. External modulation may be undesirable in some applications because of the added complexity associated with an additional device. In addition, an optical modulator introduces additional optical losses. However, external modulators have the potential of operating with low frequency chirp [13] (i.e. they introduce no undesired increase in the bandwidth of the modulated optical signal). External modulators are therefore attractive in systems where fiber dispersion may become a problem. External modulators may also find application in systems in which a number of modulated signals need to be derived from a single optical source, and in coherent optical systems requiring specialized modulation formats.

Optical modulators can be divided into two broad classes: (a) those dependent on the electro-optic effect in materials such as $LiNbO_3$ or semiconductors, and (b) those dependent on electro-absorption either in bulk semiconductor or quantum well material.

(a) Electro-Optic Modulators

An electro-optic material has a refractive index which changes with an applied electric field. The change in electric field can be used to change the phase-shift of an optical signal in a waveguide or to change the coupling between two closely-spaced optical waveguides. Using these effects, various structures can be employed to intensity modulate a CW optical signal in response to a changing voltage on an electrode contacting the electro-optic material. A prefered structure for broadband modulation uses traveling-wave electrodes [14]. The advantage of this arrangement is that it can be designed to operate at impedance levels around 50 Ω. The main limitation on performance of traveling-wave modulators is the velocity mismatch between the optical and electrical waves [14]. However, useful modulation at frequencies as high as 40 GHz has been reported in $LiNbO_3$ devices [15], along with insertion losses of the order of 3 dB.

(b) Electro-Absorption Modulators

Electro-absorption modulators make use of the dependence of band-to-band absorption in semiconductor materials on an applied electric field. The material can be a bulk direct bandgap semiconductor, in which the field-dependent absorption arises from changes in the nominal absorption edge associated with the bandgap. Alternatively, in quantum well structures, an enhanced electro-absorption effect known as the quantum-confined Stark effect can be used [16,17].

The electric field in electro-absorption modulators is applied across a reverse-biased p-n junction. As a result, the modulator is a high impedance device, in which the dominant frequency-limiting effect is a capacitance in shunt with the impedance of the driver. The capacitance is made up of two components: one associated with the device junction, and one associated with the bonding pad. The bandwidth is limited by the sum of the two capacitances. In devices using semi-insulating layers adjacent to the optical waveguide, capacitances as low as $\sim$ 0.5 pF have been achieved with bandwidths as high as 10 GHz [18].

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