FIELD THEORY ANALYSIS OF DISTRIBUTED MICROWAVE EFFECTS IN HIGH SPEED SEMICONDUCTOR LASERS AND THEIR INTRCONNECTION WITH PASSIVE MICROWAVE TRANSMISSION LINES

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ABSTRACT

This paper present a rigorous field theory analysis of the distributed microwave effects in high speed semiconductor lasers by using a combination of a self-consistent complex finite difference method with the frequency-domain TLM method (FDTLM). The semiconductor laser is treated as a lossy multilayer slow-wave microstrip transmission line. The conductivity profile in the active layer is obtained by a self-consistent solution of the nonlinear semiconductor device equations. The attenuation factor, phase velocity and characteristics impedance of the semiconductor laser is presented for the unbiased and forward-biased case and compared with experimental results. On the basis of this analysis we present the interconnection effects between passive microwave transmission lines and laser diodes using airbridge or flip-chip transitions.

INTRODUCTION

High-capacity fiber optic links require semiconductor laser chips that can be modulated over a wide frequency range. Up to now 300μm long laser structures have been reported that operate at frequencies above 25GHz[1]. However, modulation frequencies far beyond 30GHz are required to accommodate 40Gbit/s transmission rates. The problem at such high modulation frequencies is that the wavelengths becomes compatible with the laser dimensions and may cause microwave distributed effects which can not be neglected. This was found experimentally in a recent paper by Tauber et.al. [1]. The authors reported that the laser diode investigated exhibited a slow-wave effect, was very lossy and dispersive. Unfortunately, the equivalent network model described in [1] to analyze the microwave effect in semiconductor lasers is only of limited value. A more accurate characterization of the distributed microwave effects in laser diodes is very important for integration and interconnection with passive microwave feed networks. Therefore, in this paper we present a field-theoretical analysis of a class of separate confinement heterostructure (SCH) semiconductor laser diodes and their distributed microwave effects. The results are compared with experimental data from [1]. Furthermore, we investigate the electrical performance of the airbridge and the flip-chip interconnect between a passive microwave transmission line and the laser structure (Fig.1). This is the first time that such an analysis is reported.

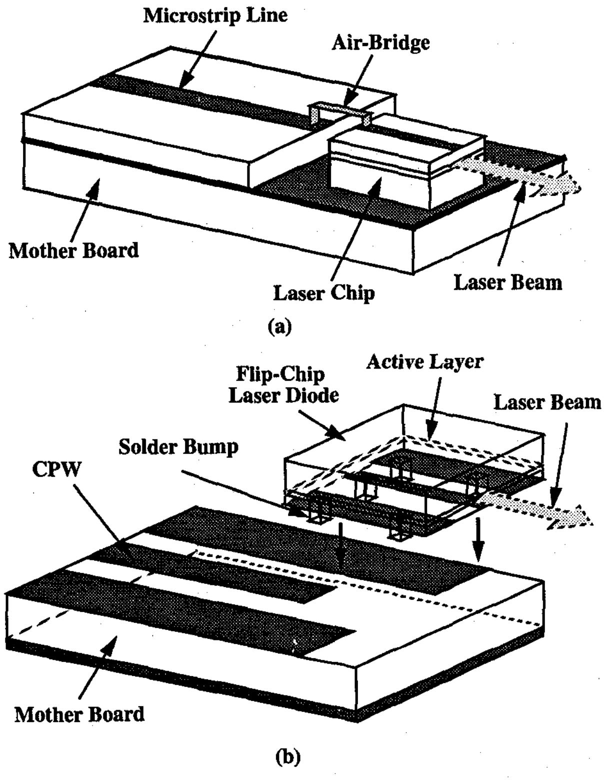

Fig.1 (a) The airbridge and (b) flip-chip assembly approach Connection between semiconductor laser chip and microwave transmission line.

THEORY

Fig. 2 shows the semiconductor laser configuration with a separate confinement heterostructure (SCH). An

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optical slab waveguide is formed by the active region sandwiched between two cladding layers. From a microwave perspective this SCH laser diode represents a lossy and dispersive slow-wave transmission line, because of the high doping in the p- and n- cladding layers and the high injected electron-hole pair density in the active region. When biased, the injection current spreads from the contact and the p-cladding into the active layer. The resulting potential distribution in the passive cladding layer is described by Laplace's equation [2]:

$$\nabla^2 V = 0 \qquad (1)$$

From the potential distribution, the current density injected into the active region can be determined. This injected current acts as the source of the carrier distribution in the active region in which the continuity of the quasi-Fermi potential and charge neutrality may be assumed. Along the device lateral direction the injected carrier density in the active region is described by the carrier rate equation, which may be written as follows [3]:

$$D_{eff}\nabla^2 n - Bn^2 - \frac{c}{n_0} g S_0 \Psi + \frac{J}{qt} = 0 \qquad (2)$$

where we assume $\partial n/\partial t = 0$ (steady-state condition). D_{eff} is the effective diffusion constant, n the local carrier density, B the carrier recombination constant, c the speed of light in free space, n_0 the background refractive index of the active region. g the gain profile across the active region, q the electronic charge, t the active layer thickness, J the local injected current density, S_0 the average photon density in the optical cavity, and Ψ the normalized optical intensity. Equation (2) assumes that the active layer thickness t is small compared to the carrier diffusion length. This means that no recombination occurs outside the active region. Equation (1)~(2) can be solved self-consistently by using the complex finite difference method (CFDM) [2,3].

After the electron-hole pair concentration n is obtained the conductivity in the active region is readily found [4]:

$$\sigma_a = q(\mu_n + \mu_p)\, n \qquad (3)$$

where μ_n and μ_p are the mobility of electrons and holes, respectively.

The conductivity profile given in (3) is then used to represent the active layer as a lateral inhomogeneous substrate layer when we analyze the laser diode as a microwave structure employing the frequency-domain TLM (FDTLM) method. The FDTLM method is a rigorous full wave technique which can be used for 2D and 3D discontinuity problems. A detailed description of the FDTLM method has been given in [5] and will not be repeated for brevity.

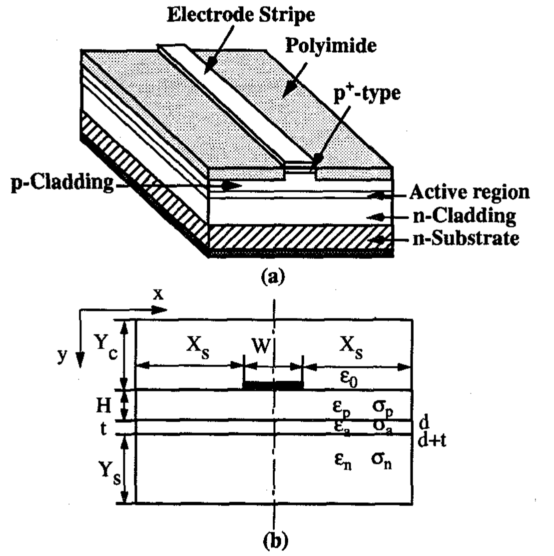

Fig.2 (a) Typical high speed semiconductor laser diode with separate confinement heterostructure (SCH). (b) A three layers lossy microstrip transmission line model for semiconductor lasers.

NUMERICAL RESULTS

The transition of the semiconductor laser to either a microstrip or coplanar transmission line, as shown in Fig. 1, presents a truly three dimensional circuit discontinuity. The modulation signal and the DC biasing current are fed into the laser chip by either an airbridge or a flip-chip interconnect. Besides its wideband performance, the flip-chip transition is of significant interest, because it may also alleviate the mechanical alignment problems in focussing the laser beam into a single mode fiber. In view of the electrical performance, however, the low input impedance of the laser diode may be difficult to match, because the line dimensions may be impossible to realize in either CPW or microstrip and thus abrupt discontinuities between both transmission lines may lead to significant reflections. Before we investigate this problem in more detail we will first present results for the laser diode as an active transmission lines.

1. Propagation Parameters and Characteristics Impedance

Because the current flows through several layers of substrate with different properties, it is certainly highly dispersive, very lossy and must exhibit a slow-wave behaviour. The attenuation and phase velocity for the laser structure considered here is obtained from the FDTLM analysis. Results for the microwave attenuation of the structure are shown in Fig.3(a). In comparison to the measured results for the unbiased and forward biased case, the difference to the theoretical results are relatively small. The same can be said about the phase velocity in Fig.3(b). The curves for the biased and unbiased case are very close, which also confirmed by the measurements. Also the tendency over the frequency is the same. Comparing both figures it is evident that the attenuation is much more affected by the bias current than the propagation constant. A possible explanation for this is that at forward bias, the conductivity in the undoped active layer increases significantly due to the high electron-hole pair injection, which is approximately 2 ~ $3x10^{18}$ cm^{-3}. This will result in a significant increase in the attenuation. However, its effect on the phase constant must be small because this highly conductive layer is very thin compared to the cladding layers. With respect to the results of Fig.3, it should be noted that we do not know the exact cross-section of the structure measured in[1], Our theoretical model (Fig.2a) may be too simple. However, we believe that although the absolute value for the attenuation and phase constant may change depending on the layers and their characteristics, the general tendency of the results will remain the same. The algorithm developed here can take into account more complex structures then the one shown in Fig.2a.

Measurement results for the characteristic impedance are not available. The theoretical results are, however, according to our expectations and shown in Fig.4 for the real and imaginary part. The increase in the characteristic impedance values with frequency is probably due to the skin effect in the various layers of the structure. The influence of the bias current on the characteristic impedance is not significant. The real part seems to be more affected because in forward bias more carriers are injected into the active layer which increases its conductivity. This equivalently short-circuits the lower n-doped layer in the substrate, reducing the real part of the characteristic impedance.

2. Interconnection of laser diode with passive transmission line

Interconnecting the laser chip with a microstrip transmission line by an airbridge is simulated in Fig.5. The operating frequency is assumed to be 25GHz and the laser chip emits light at 980nm. For a constant airbridge length and varying strip length of the laser we first see a relatively high return loss. On one hand this due to the airbridge length, which is quite inductive at that frequency. On the other hand we have assumed a 50Ω microstrip transmission line which represents quite a mismatch to the low-impedance laser chip. By varying the laser length the return loss can be influenced somewhat, but not very much. The main reason for this is that the impedance mismatch and inductive effect of the airbridge is so strong that what ever standing wave effect can build up on the lossy laser electrode is buried in the return loss.

A more visible effect can be observed when we increase the gap between the laser chip and the motherboard, which in turn increases the length of the airbridge. This is shown in Fig.5(b). There appears to be an optimum gap of 5μm between both transmission lines, or a total length of the airbridge of 14μm.

The performance of the S_{11} of the airbridge and the flip-chip interconnection assembly over the frequency range of 0 to 40 GHz is presented in Fig.6. The flip-chip result presents the interconnection between the laser diode and a CPW transmission line. From Fig.6 it is evident that the flip-chip interconnection assembly is more suitable for high frequencies applications.

CONCLUSIONS

We have presented a rigorous field theory analysis of the distributed microwave effects in high speed semiconductor lasers by using a unique combination of a self-consistent complex finite difference method with the frequency-domain TLM method (FDTLM). The semiconductor lasers is treated as a highly lossy and slow-wave microstrip transmission line with multilayer inhomogeneous substrate. The conductivity profile in the laser active layer is obtained from a self-consistent solution to the nonlinear semiconductor device equations and then used as the input parameter in the FDTLM analysis. The attenuation factor, phase velocity and characteristics impedance of the semiconductor lasers are calculated and compared with measured data. It is found that the calculated results confirm our theoretical prediction. The effects of the length of the laser cavity and the airbridge to interconnect the laser chip with a microwave motherboard has been investigated. It was found that at 25GHz the impedance mismatch between motherboard and laser chip as well as the inductive effect of the airbridge introduces prohibitively large reflections. The flip-chip interconnection alleviates this problem to some extend.

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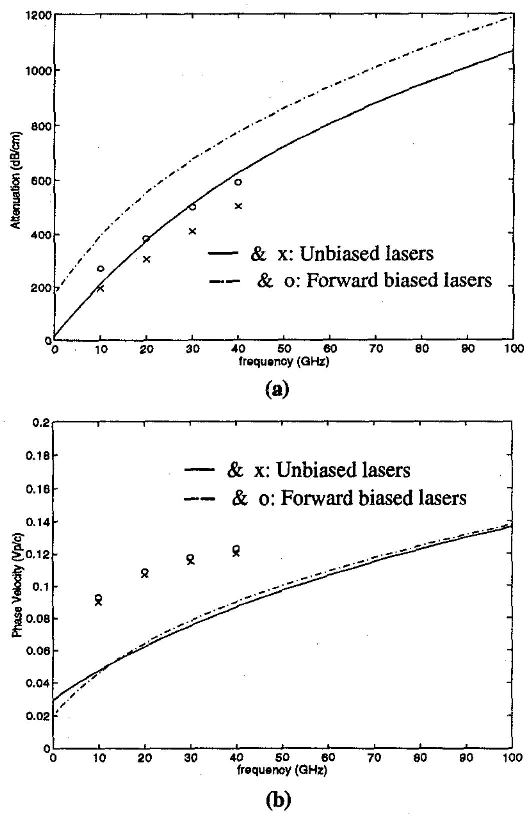

Fig.3 (a) Microwave attenuation per unit length vs. frequency. (b) Phase velocity, normalized to speed of light in free space, vs. frequency. The lines represent numerical results using FDTLM and the points represent measured values basec on measurements from [1].

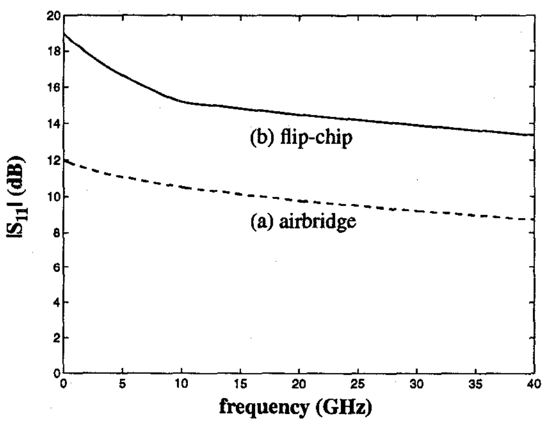

Fig.6 The S-parameters of the (a) airbridge and (b) flip-chip interconnect assembly as a function of the frequency.

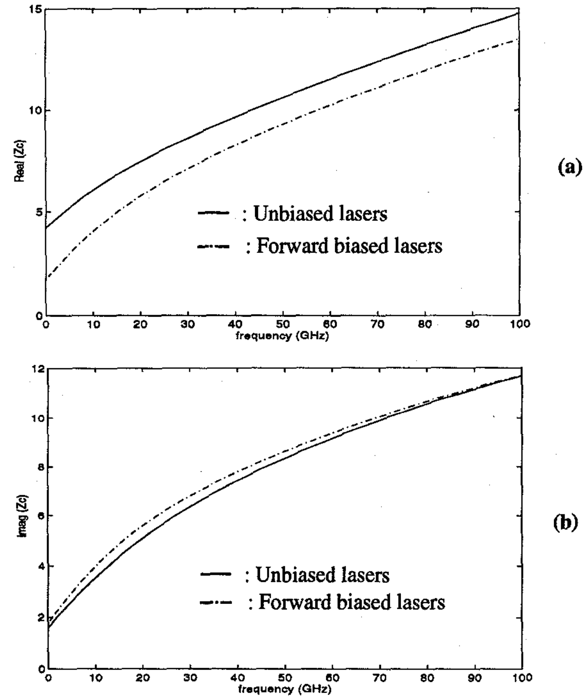

Fig.4 (a) Real part of the characteristics impedance of the laser diode vs. frequency. (b) Imaginary part of the characteristics impedance vs. frequency. The lines represent the numerical results using the FDTLM analysis.

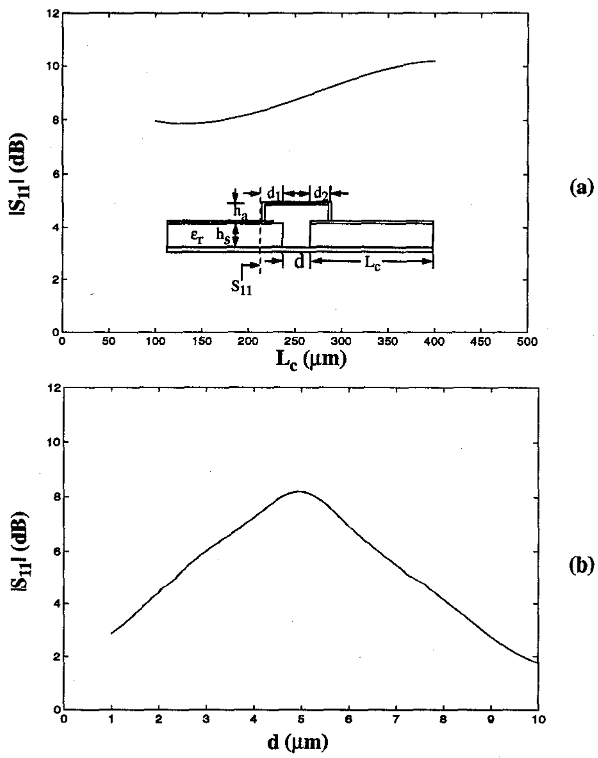

Fig.5The S-parameters of the airbridge interconnect assembly (d_1=d_2=3µm, h_a=2µm, h_s=100µm, ε_r=12.9). (a) S_{11} as a function of the length L_c of the laser chip. (b) S_{11} as a function of the gap d between the mother board and the laser chip (L_c=200µm).