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Simple signal path technique for matching circuit in packaged semiconductor diode laser

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Improvement in frequency bandwidth of a packaged diode laser is investigated by the circuit impedance matching. To overcome the structural limitation of the electronic package for high frequencies, employing conventional lumped element impedance matching technique in conjunction with the manipulation of signal path of the package connections showed significant enhancement for 3-dB bandwidth to more than 6 GHz.

Keywords: bandwidth, frequency response, circuit modelling, diode laser, device packaging.

1. Introduction

Recently, strong demands for higher throughput and drastic price reduction of optical components have made a fiber-optic data transmission a commodity in mainframe computer systems or in local area and subscriber networks. Since the uprising new optical communication market is focused on the access network such as fiber-to-the-home (FTTH), free space optics (FSO), radio over fiber (RoF) systems, and other optical transmission systems fused with wireless communications, optical modules for higher bit-rate of more than 1 Gbit/s whether used in Ethernet or SDH/SONET, and for low-cost and compactness are required. Accounting these various last mile solutions, transistor outline (TO)-can packaged laser module provides the solution for cheap and compact light source. To date, many experimental and/or theoretical researches in high bit rate transmission systems offered the way of impedance matching to the laser module for various types of packaging [1,2]. However, conventional method for parameter extraction of laser package was a relatively complicated procedure with measuring and fitting the characteristics of scattering parameters (S-parameters) [3,4]. Furthermore, they had ignored the parasitic components of the packages by inserting just series chip resistor or had used the distributed type elements by designing stub transformers which could be used in specified band applications [5–9].

In this work, frequency response of conventional TO-can laser module has been improved by changing the signal path for widening the 3-dB frequency bandwidth, where the path could be modified with simply changing the internal RF signal path of module package. The equivalent circuit model of a laser module is precisely extracted from the package, and in order to improve the characteristics of frequency response, the impedance matching circuit is applied to the device as well as transforming the package structure. Namely, the computations for circuital level analysis are exploited for the potential to the broadband impedance matching with modifying the interconnections in the diode package.

2. Device modelling and results

The cross sectional view of a laser diode chip is shown in Fig. 1(a) and the equivalent circuit models for each junction, interface, and contact are given in Fig. 1(b). There are combination for the series resistance of the semiconductor layers which are doped with impurities from the ohmic metal to the active layer in the middle of the epitaxial layers and the p-n junctions are formed for the n-type and p-type InP contacts in three ways (one in vertical way and two in horizontal direction). The blocking SiO_2 layer also acts as dielectric material that generates the capacitance between the upper and lower layers in between. Moreover, p-n junctions are formed between different types of InP doping layers at the edges of the trench structure and the semi-insulating (SI) InP layers also function as the dielectric layer of the parasitic capacitor. However, it was not only impossible but also unnecessary to use this exact equivalent model where the parameters are not achievable. Instead throughout the following analysis, the well-known diode model of a resistor with parallel capacitance and a series parasitic inductance for bonding wire if presented with the diode chip (R//C-L) is used which could be identical if the model is converted to a series resistance and an input capacitance instead.

The three-dimensional view of the TO can package is illustrated in Fig. 2 where a package consists of three major

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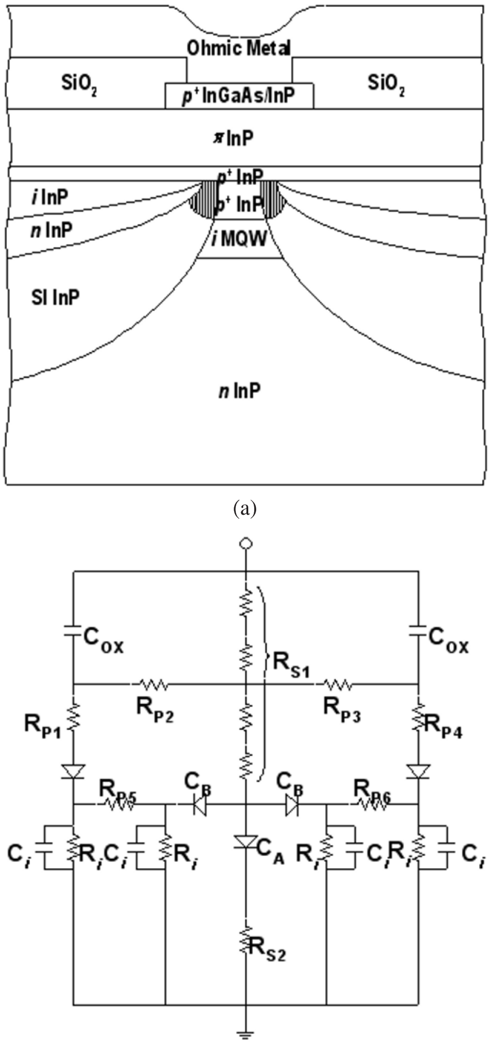

Fig. 1. Cross section of laser diode (a) and equivalent circuit model (b).

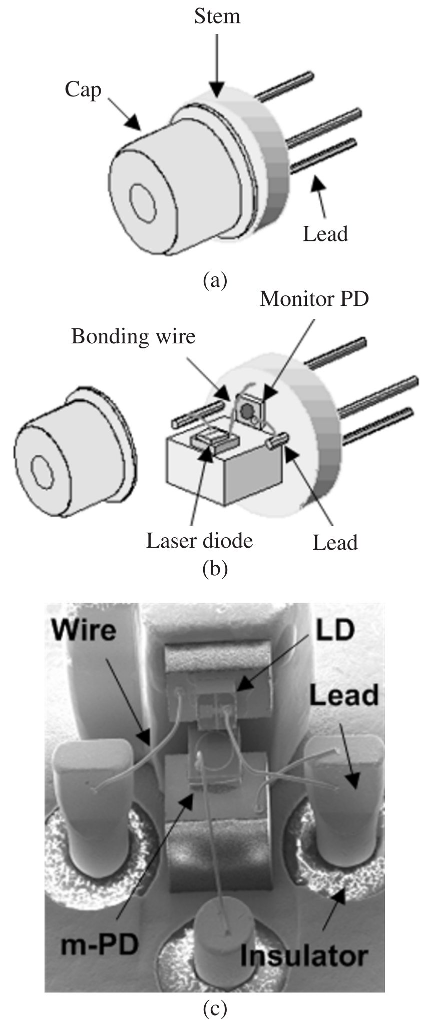

Fig. 2. TO can package outlook (a), package inner view (b), and SEM image of package (c).

parts such as cap (cover), stem (main body), and leads (pins) for the outlook as in Fig. 2(a). These lead pins are electrically insulated to each other for the use of interconnecting different components to the outer circuits which could be three or four depending on the pin configurations and common pin sharing a certain lead. The laser diode is placed in the cap where the diode is die attached to the main body which is wired to the pins above the stem as well as monitoring photo diode (m-PD) as a reference to the emission output power shown in Fig. 2(b) filled within a N_2 gas for protection (the cap and the stem are combined by a cap welding process under N_2 environment chamber). There is also a scanning electron microscope (SEM) image in Fig. 2(c) for the internal micro package structure where we could observe all the components in the above schematic views including the insulating rings (dielectric material) around each of the lead pins.

The side view of a conventional TO-can laser module and its corresponding circuit model are in Fig. 3(a) where the bonding wire and package leads are considered as inductors, dielectric spaces form the capacitors between the metal plate and glass powder (which acts as dielectric layer) for electrical insulation, and the laser diode (LD) consists of parallel combination of resistor and capacitor [Fig. 3(b)] is for the improved package interconnections which will be discussed later. The overall equivalent circuit model is given in Fig. 4(a) and the corresponding values of the capacitances for a diode (C_d = 0.3 pF) and package parts ($C2 = C3$ = 0.15 pF, $C1$ = 0.7 pF) are estimated from the following equation of parallel plate capacitance,

$$C = \varepsilon \frac{A}{d}$$

where, ε is the dielectric constant, A is the area, and d is the width or distance of the dielectric layer. The parasitic inductances are predicted from the length and the thickness of the bonding wire ($L1$ = 1 nH) and the package leads ($L2 = L3$ = 5 nH) where, in brief, longer and thinner one corresponds to the larger inductance which was comparable to the previous analyses [2,3] and do not lose the validity of the component values for computation in general. The RF signal flows from the middle pin (RF signal IN) of the

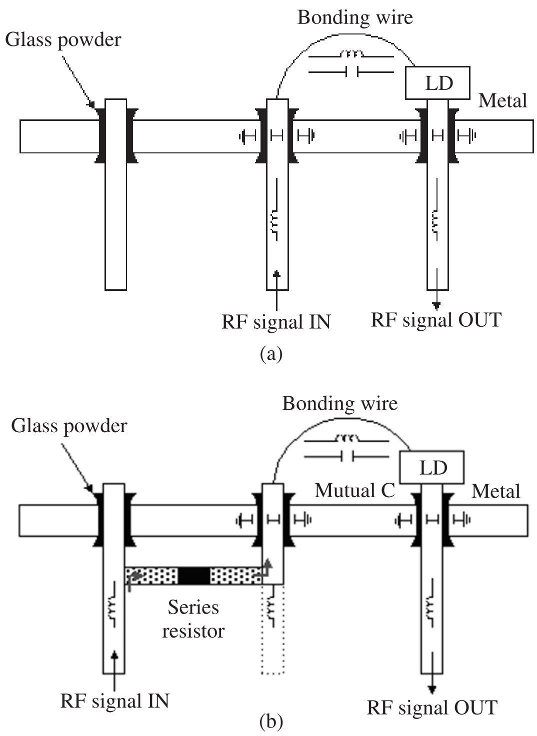

Fig. 3. Conventional TO-can laser package schematic side-view (a) and modified signal path for laser package schematic side-view (b).

package to the right one (RF signal OUT) where the RF signal modulates the diode following the signal path. From the SPICE simulation results which were obtained by dividing the power consumed at the diode part by the input signal power (S_{21}), without comprising matching circuit, the 3-dB frequency bandwidth of the package itself is less than 850 MHz and the response curve rapidly changes as the frequency increases. These limitations on the frequency response are mainly due to the capacitance in the TO-can laser module acting as a low-pass filter.

Therefore, frequency response of TO-can laser module can be improved to achieve extended 3-dB frequency bandwidth by adding inductive components to cancel out the capacitance in packages as in Fig. 4(b). Due to the opposite phase characteristics between reactances of the capacitance ($-j/X_C$) and the inductance ($+jX_L$), inductive components compensate the reduction of a frequency response of the laser TO package induced from the parasitic capacitances which determines the knee frequency of the bandwidth curve. It can be added by bonding wires, but we cannot obtain a consistent inductance value. Instead, in order to realize the inductance, microwave strip lines could be implemented. Furthermore, to insert the matching circuit nearest to the signal path, the package structure is changed as shown in Fig. 3(b) which is added with the inductive components and the matching series resistor. This could be achieved by the surface mount technology on the printed circuit board (PCB) to attach the package to the circuitary subsystems. For broadband impedance matching the series resistor is desirable in that the resistance does not depend

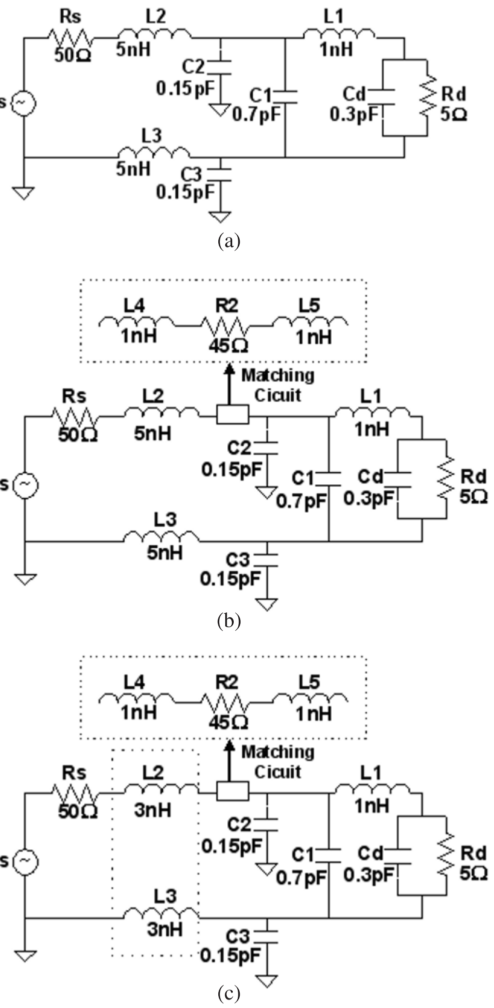

Fig. 4. Equivalent circuit model (a), conventional package (b), and impedance matching circuit modified package (c).

on a specified frequency band compared to the frequency dependent reactances ($+j\omega L$, $-j/(\omega C)$). The frequency bandwidth including the impedance matching circuit to the TO-can laser module is 1.46 GHz not suitable to use for 2.5 Gb/s systems. The encapsulated box is the inserted matching circuit where the resistor is a series resistance (R2 = 45 Ω) that matches to the 50 Ω source if combined with the diode resistance, and the inductive elements are optimized for the results ($L4 = L5 = 1$ nH).

Even though the inductive elements $L4$ and $L5$ are less than 1 nH, the frequency response does not change. Hence, in order to obtain the larger, 3-dB frequency bandwidth, other composing elements of the laser module should be adjusted. One simple way is to vary the lead inductance $L2$ and $L3$ of the module by reducing the length of package lead. The optimization of the frequency response is executed by changing the values of matching inductive elements where it is optimized also when $L4 = L5 = 1$ nH. Simulation result provides 3-dB frequency bandwidth more than 6 GHz for Fig. 4(c) with decreased package leads' inductance values from the initial 5 nH to shortened 3 nH.

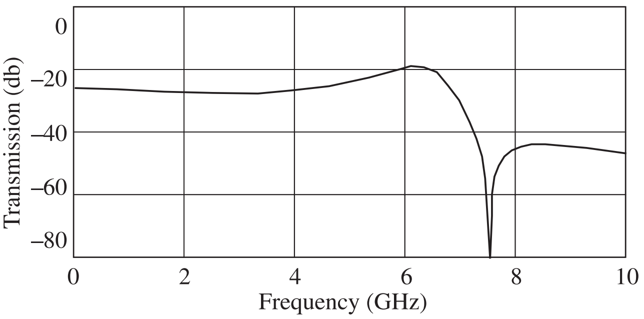

Fig. 5. Result of frequency response from microwave circuit simulator (SERENADE).

For accurate high-frequency RF simulation, microwave circuit simulator SERENADE has been used to confirm the SPICE simulation result. In case of one-port device, only the S_{11} or the return loss could be measured as a criterion for evaluation where the RF input is the incident power or voltage whereas the RF output is the returning one at the same microwave port. Whereas, if the consumed voltage at the diode is defined, the device could be modelled as a two-port one so that the transmission or the signal output power of the diode divided by the input power, i.e., S_{21}, is possible to explore for the observation of the 3-dB bandwidth of the device. The result in Fig. 5 verifies the SPICE simulation where the bandwidth is more than 6 GHz with the curve flattened in 1.7 dB up to 2.9 GHz. This result is also compatible to the similar previous experimental one, though the former result shows much smaller bandwidth of 2.3 GHz without internal package modification (it was only performed with simple reduction in lead length), in that the 3-dB bandwidth extension was achieved by shortening lead length of the TO package [4]. Finally, the flow processes of the package change, circuit improvement, and simulations results are summarized in Fig. 6 through a sequential chart form for convenient comparison.

3. Conclusions

In summary, a method of circuit impedance matching was proposed and analyzed not only by inserting external circuit elements but also by adjusting the internal signal path structure of conventional TO-can laser package to improve the frequency response. By controlling the package leads' inductances reduced to 3 nH and the matching inductances for compensating the negative reactance of the parasitic capacitance to 1 nH achieved by the microstrip lines at both sides of the series resistor for broadband impedance matching, circuit simulation results show that significant improvement of the 3-dB frequency bandwidth of larger than 6 GHz is obtained flattened within 1.7 dB up to 2.9 GHz using the proposed matching approach. This approach provides a novel analytical way of enhancing the characteristics of frequency response of the TO-can packaged laser module with external matching circuits without losing consistency to the previous experimental results.

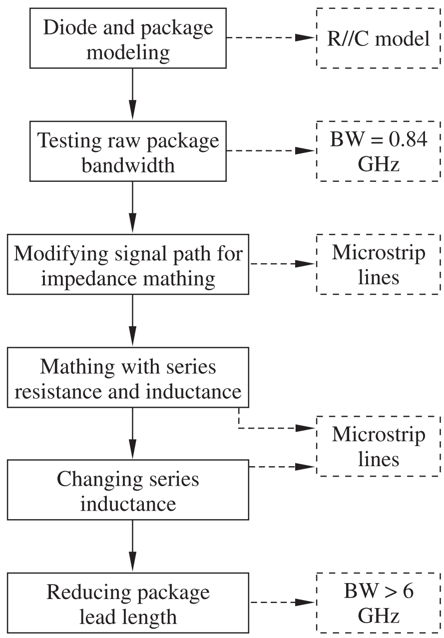

Fig. 6. Flow chart for analysis and corresponding results.

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