Broad-Band Reactive Matching of High-Speed Directly Modulated Laser Diodes

Charles L. Goldsmith, *Member, IEEE*, and Brad Kanack, *Member, IEEE*

Abstract—**The design and demonstration of an octave bandwidth impedance matching network for directly modulated diode lasers is focused upon. Compact semi-lumped matching structures have been designed and fabricated at microwave frequencies with near theoretical performance. The laser was matched to 50 Ω over the 2–4-GHz band, achieving greater than 13-dB return loss and a dramatic 10-dB improvement in fiber link insertion loss and sensitivity. Excellent agreement was obtained between measured and simulated fiber link performance.**

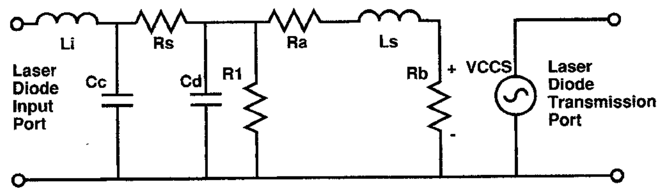

Fig. 1. Small signal model for the laser diode including packaging parasitics [9]. The voltage controlled current source is used to normalize the model to the signal contained on the optical carrier.

I. Introduction

SEVERAL papers [1]–[3] have reported significant improvements in fiber link insertion loss and sensitivity over narrow bandwidths using reactive matching. However, using these same techniques over broad bandwidths has proven more elusive. Previous papers [4], [5] have expounded on the potential of broadband reactive matching through the use of simulations. However, only two researchers to date have described demonstrated results [6], [7]. Both papers reported roughly 5–6 dB minimum return losses over octave bandwidths. This letter presents significantly improved matching results over the 2–4-GHz band, and gives the specific details and measurements used to obtain these results.

The specific laser used for this investigation is a Lasertron QLM3S900 straight-wall buried-heterostructure laser rated to 10 GHz. First, the laser was characterized to create an accurate two-port model. Afterwards, a Chebyshev pseudo-bandpass matching structure was designed and constructed to impedance match to the low laser impedance. Our results show that an order of magnitude improvement in fiber link insertion loss can be obtained over a broad bandwidth with proper matching of the laser diode. Comparisons of measured and modeled results are given for both impedance match and fiber link performance, with overall results very close to an ideal matching response.

II. Modeling

Typically, a one-port small-signal model is all that is required to impedance match a diode. However, a full two-port model affords the capability of simulating both the input impedance and transmission response of a laser diode. This provides extra insight into the effects of the impedance matching circuit on fiber link performance. For our particular device, a bias-dependent two-port model was generated to provide the capability of optimizing the matching and transmission response of the link as a function of laser bias.

The model for this laser is similar to that originally proposed by Tucker [8]. The specific characterization and modeling of this particular laser was discussed in our previous paper [9]. The full model of the laser is reproduced in Fig. 1, and incorporates parasitic packaging effects (L_i, C_c), laser spreading and contact resistance (R_s), laser junction effects (C_d, R_1), and rate equation elements (R_a, L_s, R_b). This model was developed and verified by two-port s-parameter measurements of the overall fiber link, showing a tight fit between measured and modeled transmission and impedance responses.

An analysis of the Lasertron QLM3S900 laser diode shows that its input impedance is dominated by parasitic input resistance and inductance. Above threshold, the laser input impedance is essentially 4.25 Ω in series with 0.12 nH. These values were used to perform the preliminary impedance matching design and evaluation.

III. Matching Structure

The bandpass matching structure chosen for this design was first proposed by Matthaei in 1964 [10]. Chebyshev impedance transforming networks employ low-pass elements designed to provide a pseudo-bandpass response. The low-pass topology of these networks provides a distinct advantage for laying out microwave lumped and semi-lumped bandpass filters. Realization of series-L/shunt-C ladder structures are far easier than the typical series and shunt LC resonator structures of normal lumped-element bandpass filters. Additionally, lumped-element filters occupy much less length than the traditional quarter-wave distributed networks at low microwave frequencies. A schematic representation of a general sixth order network and its response is shown in Fig. 2. The circuit elements of this network were designed using the tables of normalized values provided in [10]. Our laser matching

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The authors are with Texas Instruments, Inc., P.O. Box 655474, M/S 245, Dallas, TX 75265.

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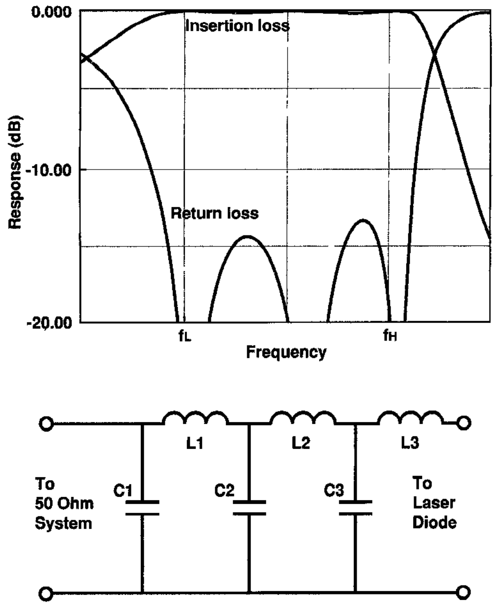

Fig. 2. Circuit topology and response of the Chebyshev impedance transforming network [10]. This low-pass topology is designed to exhibit a pseudo-bandpass response.

structure was designed to match from 50 Ω to 4.25 Ω over the 2–4-GHz band. To achieve this performance, a fractional bandwidth $w = 0.8$ and transformation ratio $r = 12.5$ were used to interpolate the normalized capacitor and inductor values from the tables.

The microwave filter was designed by scaling the normalized elements to 50 Ω and $f_o = 3$ GHz. The resulting element values are $Rs = 50$ Ω, $C1 = 1.51$ pF, $L1 = 1.62$ nH, $C2 = 4.12$ pF, $L2 = 0.824$ nH, $C3 = 8.10$ pF, $L3 = 0.302$ nH, and $Rl = 4.0$ Ω. An analysis of this ideal network yields approximately 0.20-dB in-band insertion loss, which corresponds to a 13.5-dB maximum in-band return loss. Using the two-port laser model, the filter elements were re-optimized to account for the laser parasitic reactances. Afterwards, the inductors were converted to transmission line elements [11]. The distributed inductors provide a more producible means of achieving the desired inductances compared to using wire wound inductors. Additional elements were added to provide bias connection to the laser and bias decoupling from the 50-Ω input. The final circuit elements were adjusted to compensate for laser diode parasitic effects as well as accommodate off-the-shelf capacitor values. The final circuit schematic is shown in Fig. 3.

IV. Construction

When integrating the laser matching circuit with the laser itself, it is imperative that the laser diode and matching structure be positioned as close together as possible. Eliminating unnecessary line length prevents the impedance of the laser from being rotated around the Smith Chart, changing its effective input impedance. To accomplish this, the matching network was laid out to occupy as small an area as possible, allowing it to be directly inserted into the laser module package.

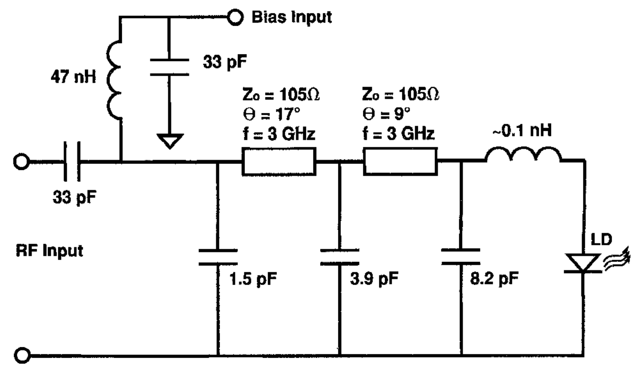

Fig. 3. Complete laser matching network, including dc block and biasing circuit.

Our design occupied an area of only 0.0225 in^2, or 0.15 in by 0.15 in. The circuit was fabricated on a 0.015-in thick alumina substrate ($\varepsilon_r = 9.8$). Chip capacitors were epoxy mounted onto the substrate, with plated-through via holes supplying the ground connections. Bond wires were used to interconnect the capacitors and the distributed inductors. A ribbon connection was made to the 50-Ω input transmission line, and bond wires were used to connect the matching structure to the laser.

V. Results

Fig. 4 presents the measured and modeled return loss and transmission response for both resistive and reactive matching. The simulated results employ the previously described two-port laser model of the Lasertron QLM3S900 laser. The measured results were taken on an HP8757 scalar network analyzer. In these measurements, the fiber is tightly coupled to the laser, while the detector is only loosely coupled. The optical coupling was equalized during all measurements by adjusting for a constant dc photodetector current.

The results of Fig. 4 demonstrate excellent matching performance across the 2–4 GHz band. The laser matching structure exhibits a 13-dB worst case return loss across the band. The transmission response shows 10 dB, an order of magnitude, improvement in insertion loss for reactive matching over resistive matching. The 10-dB decrease in insertion loss correlates well with the theoretical 11 dB ($10 \log 50/4.25$) improvement possible for a 4-Ω impedance in a 50-Ω system. The response of this network was achieved with little post-assembly tuning of the matching structure. Subsequent networks and lasers have been integrated with similar results.

It should also be noticed that the simulated response tracks the measured response quite well. Minor deviations in the measured return loss response do occur due to various packaging parasitics. However, these results certainly validate the accuracy of the model and demonstrate that first pass success is achievable with careful laser modeling and matching structure design.

VI. Conclusion

We have successfully demonstrated broadband microwave matching of a high speed laser diode. An accurate two-

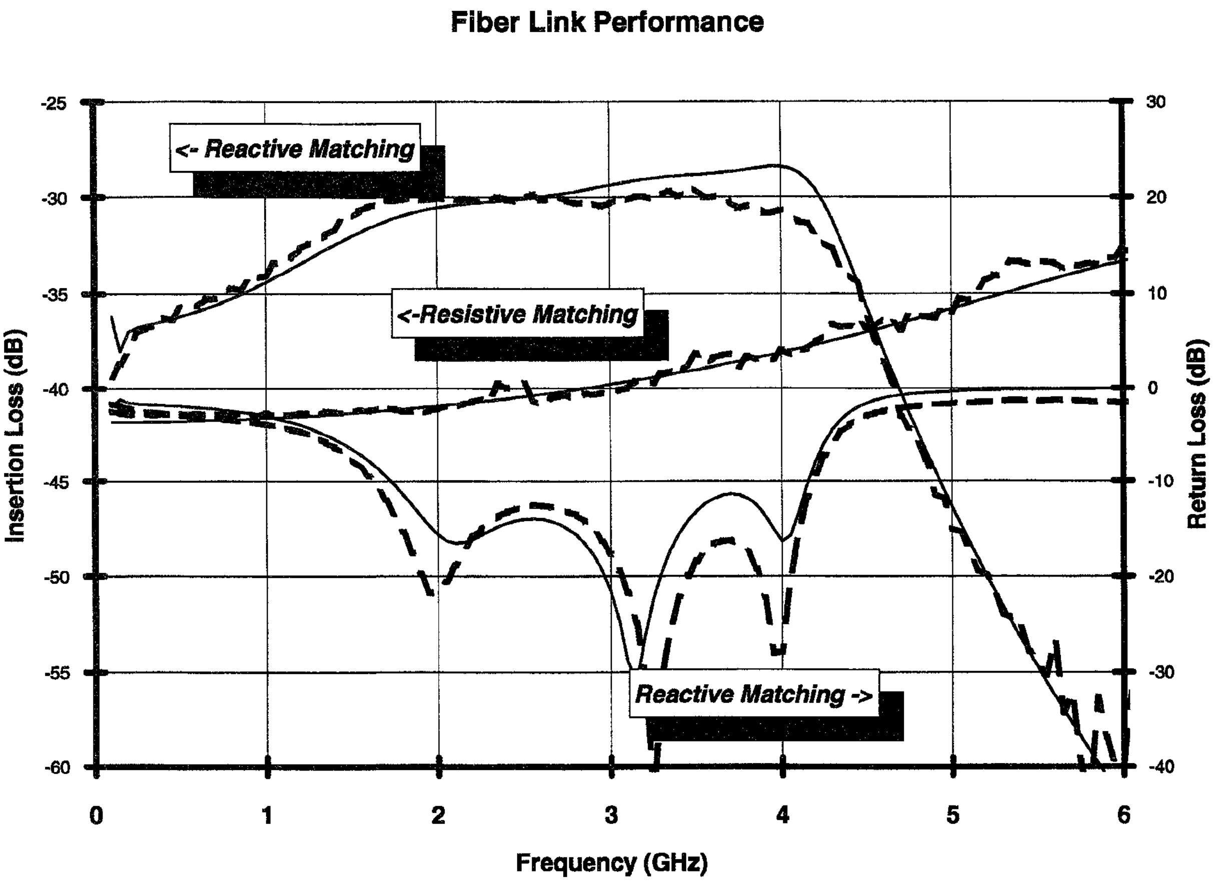

Fig. 4. Final measured (dashed) and modeled (solid) insertion loss and return loss for the resistively and reactively matched laser diode. The insertion loss is improved by 10 dB with reactive matching and has a 13-dB minimum return loss.

port model was constructed to model the impedance and transmission properties of the laser. This model was used in the successful design of a six- element pseudo-bandpass network to match from 50 Ω to the low impedance of the laser. The resulting network was compact enough to be integrated into a commercially available high speed laser module, achieving better than 13-dB return loss across an octave bandwidth, with a 10-dB improvement in link insertion loss and sensitivity.

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