TABLE I
THE COEFFICIENTS c_0, c_1, c_2, AND c_3 IN THE TAYLOR SERIES EXPANSION FOR THE INTERFEROMETRIC (INT), STANDARD 2×2 DIRECTIONAL COUPLER (DC), AND THE 1×2 y-FED DIRECTIONAL COUPLER (Y-FED) FOR THE BIAS POINT CORRESPONDING TO MAXIMALLY LINEAR RESPONSE $c_2 = 0$

MOD TYPE	BIAS POINT V/V_s	COEFFICIENT				P_{3IM} (dBc) • 4% OMD
		c_0	c_1	c_2	c_3	
INT	0.5	0 5	-1.57	0	2.58	-74.0
DC	0 439	0 536	-1.65	0	3.23	-72.0
Y-FED	0.0	0.5	-1.61	0	2.89	-73.6

Also given is the power at each of the third-order intermodulation frequencies relative to the power at the carrier frequency for 4% optical modulation depth

performance, the y-fed Ti:$LiNbO_3$ waveguide modulator structures offer the potential of operating to significantly higher optical power levels. These structures launch and maintain nearly equal time-averaged optical powers into both waveguides. The y-fed directional coupler and the y-fed interferometer employing a 3 dB coupler (in place of the y-combiner of a standard interferometer) at the output have the further advantage that two signals are immediately available for transmission.

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Novel Wide-Bandwidth Matching Technique for Laser Diodes

A GHIASI AND A. GOPINATH, FELLOW, IEEE

***Abstract* — This paper describes a low-loss microstrip matching circuit with large bandwidth for connecting a laser diode of nominal impedance of 2 Ω to a 50 Ω system. The technique utilizes a microstrip Chebyshev transformer without very wide line widths to obtain the match at a center frequency of 10.5 GHz with a bandwidth of 9 GHz, an insertion loss of less than 1.5 dB, and a reflection coefficient of better than −10 dB.**

I. INTRODUCTION

High-speed optical modulation of laser diodes is currently of interest in optically controlled phased array radar [1], and in high-speed optical communications systems. As the modulation frequency extends into the upper microwave and millimeter-wave frequencies, the need arises for an efficient wide-band matching circuit for the laser diode. Currently, the technique used to match the laser diode to a 50 Ω system is to introduce a series resistance to bring up the total termination impedance to 50 Ω. In the case of the Ortel SL1000, the laser is usually modeled by a 2 Ω resistance [2]; thus, the series resistance is 48 Ω. The power delivered to the laser diode is only 4% of the input drive, which is a large loss of power. This paper presents a wide-bandwidth matching circuit with lumped and distributed elements for low-

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The authors are with the Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455

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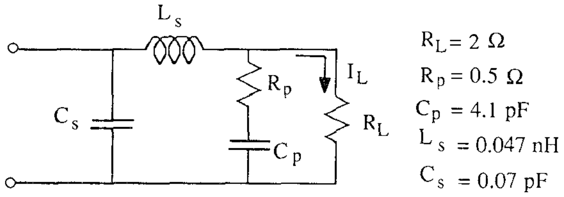

Fig. 1. The equivalent circuit of laser diode.

impedance laser diodes, and we have chosen to illustrate this technique for a diode with a nominal impedance of 2 Ω. The matching circuit proposed here has a center frequency of 10.5 GHz and a bandwidth of 9 GHz, which is a fractional bandwidth of 86%.

Matching circuits may be composed of either lumped or distributed elements. Distributed circuit elements are large at low microwave frequencies; therefore lumped elements are used for frequencies up to 3 to 5 GHz. Above these frequencies, distributed elements are suitable, and in the present paper we discuss a combination of a distributed matching circuit with lumped elements. Narrow-band (~10% bandwidth) match of these laser diodes may be obtained either by stubs or by a combination of stub and transformer [3]. For a wider bandwidth, Butterworth and Chebyshev polynomials are the common choice of approximation functions to realize multisection or taper matching transformers [4], [5]. In this case, the characteristic impedances of the sections at the outer end of the transformer are close to the impedance of the load and the source. In our particular case, matching the laser diode with a nominal impedance of 2 Ω requires very low impedances in the sections close to the laser diode. A three-step Chebyshev transformer that matches 50 Ω to 2 Ω has the quarter-wave impedances of 26, 10, and 3.8 Ω for a fractional bandwidth of 100% [4]. The last two impedances are unacceptable in a microstrip structure, as they require the line widths to be very wide; for example, a 3.8 Ω line has $w/h \approx 25.5$ on alumina substrate ($\epsilon_r = 9.9$), and transverse modes may be excited [6]. The technique used here circumvents the need for these very wide lines.

At the present time we do not have access to the Ortel laser diode discussed by Lau and Yariv [2]. Therefore we have used data given by these authors and present theoretical results.

II. Resonant Circuit

The input impedance of the laser diode (Ortel SL1000) is modeled as an equivalent RLC circuit [2] as shown in Fig. 1, and the diode has a nominal impedance of 2 Ω when forward biased beyond threshold. The series inductance L_s is primarily due to the bond wire, component C_p is due to the diffusion capacitance of the diode, and C_s is the parasitic capacitance of the structure and its package, having a typical value of less than 0.1 pF. The response of this equivalent circuit is in the form of a second-order low-pass filter with a reactive input impedance. This device is easier to match if a shunt capacitor C_L is added in parallel with C_s so that the equivalent circuit is resonant at midband. The value of the capacitor C_T, which is the parallel combination of C_s

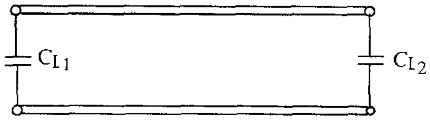

Fig. 2. Line length with two shunt capacitors.

and the additional lumped matching capacitor C_L, is given by

$$C_T = \frac{L_s - R_L^2 C_p + \omega^2 L_s C_p^2 (R_L + R_p)^2}{R_L^2 + \omega^2 \left[L_s^2 + R_L^2 C_p (R_s^2 C_p - 2L_s) \right] + \omega^4 L_s^2 C_p^2 (R_L + R_p)^2} \tag{1}$$

where $C_T = C_L + C_s \approx C_L$ and $\omega = 2\pi f_0$ is the center frequency. The 3 dB bandwidth of this resonant circuit must be larger than the desired circuit bandwidth.

Y'_{21} gives the modulation response of the laser diode, and analysis of the laser equivalent circuit driven by a generator voltage V_g with an internal impedance Z_g gives

$$Y'_{21} = \frac{I_l}{V_g} = \frac{1 + j\omega C_p R_p}{\left[1 + j\omega (R_l C_l + R_s C_p)\right]\left\{ (j\omega)^2 Z_g L_s C_T + j\omega L_s + Z_g \right\} + R_l (1 + j\omega R_s C_p)}. \tag{2}$$

Z_g is not known, but a good estimate is $Z_g \approx 2R_L$ (4 Ω in our case). Equation (2) requires, in turn, that the bond wire inductance L_s be small enough so that the bandwidth of the resonant circuit is larger than the required circuit bandwidth. When the value of C_L is known approximately, a CAD program may be used to solve for an optimized matching circuit.

III. Matching Technique

In the matching circuit to be discussed, we present a novel method of reducing the microstrip line impedance. A length of microstrip line with lumped shunt capacitors at either end reduces the line impedance to

$$Z_0 \approx \sqrt{\left(\frac{L_0}{C_{L_1} + C_{L_2} + C_d} \right)} \tag{3}$$

where L_0 and C_d are the inductance and capacitance of this length of line, and C_{L_1} and C_{L_2} are the shunt capacitors attached to this line, as shown in Fig. 2. While this technique may be used to obtain 3.8 Ω lines in principle, we choose to use smaller shunt capacitors in the circuit discussed below.

The solution for this type of extreme matching from 50 Ω to 2 Ω is to first make a transformation from 50 Ω to the lowest characteristic impedance allowed on microstrip which corresponds to w/h of about 5 ($Z_0 \approx 17.5$ Ω). This is performed by the use of a standard step or tapered transformer with sufficient bandwidth [4], [5]. The transformation from 17.5 to 2 Ω may be completed by using an extra line length in addition to the lumped capacitors, C_{L_1} and C_{L_2}, where $C_{L_1} + C_{L_2} \approx C_T \approx C_L$ and the exact ratio of C_{L_1} to C_{L_2} is computer optimized.

A third-order Chebyshev transformer was designed with impedance steps of 33, 17.5, and 9.2 Ω (100% fractional bandwidth). The transformer's lowest impedance section was replaced with the novel matching circuit while the second section was restricted to the maximum $w/h = 5$. The second circuit is a linear taper with a maximum w/h of 5. The above transformers match 50 Ω to about 15 Ω. Subsequently the last transformer section is extended by about $\lambda/16$ together with the capacitors C_{L_1} and C_{L_2} to obtain an additional phase shift [7], [8] and completes the matching from 50 Ω to 2 Ω, as shown in Figs. 3 and 4.

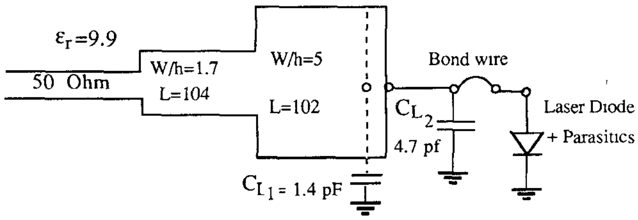

Fig 3. Layout of the novel step impedance matching circuit

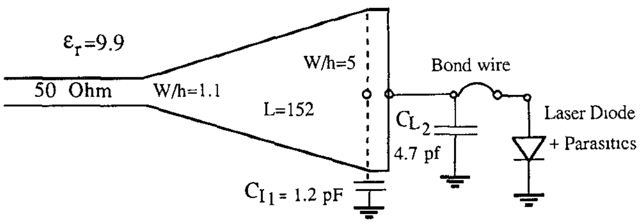

Fig 4 Layout of the novel taper impedance matching circuit

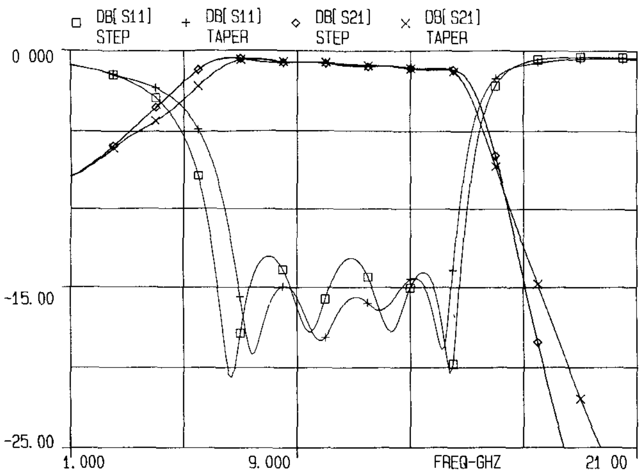

Fig. 5 Responses of the novel step and taper matching circuits

The responses of the novel matching circuits with step and linear taper distributed sections are shown in Fig. 5 and have nearly the same characteristics. The match is at a center frequency of 10.5 GHz with a bandwidth of about 9 GHz; in this band the return and insertion losses are better than 10 and 1.5 dB respectively.

Realization of this technique has not been carried out, as we do not have access to the identical diode discussed in [2]; however, work is in progress on matching other lasers. We anticipate that the hybrid implementation may suffer from additional inductances due to the bond wires used to attach the capacitors to the line, although these were accounted for in the CAD optimization [9]. A monolithic implementation will not face these problems.

IV. Conclusions

A novel matching circuit technique which matches a 2 Ω laser diode and its parasitics to the 50 Ω line has been proposed. The matching circuits have a center frequency of 10.5 GHz, a bandwidth of 9 GHz, a reflection coefficient of better than −10 dB, and an insertion loss of less than 1.5 dB.

The step and linear taper transformers have almost the same response, which suggests that the scheme is not limited by configuration. This matching scheme may also be used to match other low-impedances devices, for example, IMPATT diodes, power FET's, and bipolar transistors.

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An Infrared Fiber-Optic Radiometer for Controlled Microwave Heating

S. DRIZLIKH, A ZUR, AND A. KATZIR, SENIOR MEMBER, IEEE

***Abstract*—An infrared fiber-optic radiometer was used as a linear feedback element for noncontact temperature control of a microwave heating system. The temperature of water was monitored and maintained at about 42°C with a standard deviation of ±0.15°C and a maximum deviation of ±0.45°C. This controlled system would be very useful for medical, industrial, and domestic applications.**

I. Introduction

Accurate low-temperature (20–50°C) monitoring and control in the presence of a strong microwave (MW) field are needed in medical applications such as hypothermia [1] and hyperthermia [2]. In general, when fast volume heating is needed, MW's can be used. However, the use of conventional temperature sensors for monitoring and controlling the MW heating is complicated in a strong electromagnetic field environment.

Because of their insensitivity to electromagnetic fields, fiber-optic temperature sensors may be one way to overcome this problem. Two of the possible approaches that incorporate optical fibers are fluoroptic™ thermometry [6] and infrared (IR) radiometry [3]. The main difference between those methods is that fluoroptic thermometry requires contact between phosphor and sample while radiometry is a noncontact method. A surface of temperature T emits infrared radiation of intensity $I = AT^4$, where A is a constant. Radiometric measurements of I serve for an accurate determination of T. These measurements may well be performed via infrared-transmitting optical fibers.

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The authors are with the Applied Physics Group, School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel.
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