BROADBAND MICROWAVE MATCHING OF HIGH SPEED PHOTODIODES

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ABSTRACT

This paper discusses the successful demonstration of broadband impedance matching of high-speed photodiodes over the 2-4 GHz frequency range. The photodiodes were matched with a resistive/reactive matching technique which achieved a good output match while improving fiber link transmission response and sensitivity by as much as 6 dB.

INTRODUCTION

Presently, insertion loss and sensitivity are two prime considerations limiting the widespread use of directly-modulated fiber optic links for microwave electronic warfare applications. Much of this loss comes from the mismatch between the standard 50Ω impedance and the high impedance presented by the photodiode. Currently, commercial directly-modulated fiber links use resistive matching to achieve a good match looking back into the photodiode. Unfortunately, this form of matching dissipates much of the signal in the matching resistor.

Ideally, one would match directly from the photodiode output impedance to 50Ω. However, most PIN photodiodes run in reverse bias and have quite high resistances, generally greater than 1kΩ. Broadband matching these high resistances at microwave frequencies is impossible because of diode and packaging parasitics. An alternative to this approach is to resistively match the diode to some impedance higher than 50Ω, then reactively match from that impedance down to 50Ω. This form of matching maintains a good output match at the detector RF port while improving the output signal level by a factor of 10 Log (R_M/50) where R_M is the resistive matching impedance.

MODELING

Accurate reactive matching of any device requires a good electrical model. For this particular application, a two-port small-signal model was generated to analyze responsivity in mA/mW. R_j and C_j represent the reversed biased junction impedance, R_s is the series spreading resistance to the junction, and C_p and L_p are the parasitic capacitance and inductance of the photodiode submount. Most of these model values can be extracted though a series of simple s-parameter measurements and manipulations.

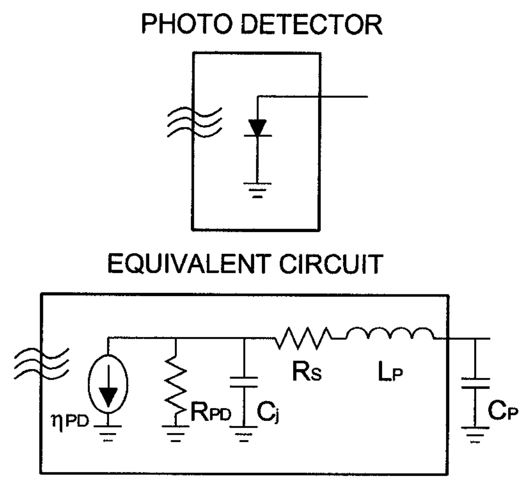

Figure 1. Photodiode equivalent circuit.

The elements C_j, R_s, L_p, and C_p are the major electrical elements which determine the input impedance of the diode. The elements C_j, R_s, and L_p form a series resonant circuit which can be extracted using the DeLoach technique [1] commonly used to extract the gate capacitance of FETs. First, the diode is measured on a vector network analyzer which, through TRL calibration, de-embeds up to the photodiode mount. The measured s-parameters then describe the diode and its submount alone. Next, the s-parameters are loaded into a circuit simulator and connected in shunt with a two-port 50Ω line as shown in Figure 2. This configuration simulates the DeLoach measurements previously mentioned. The resulting transmission response looks like that shown in Figure 2. The response of this network can be compared to the theoretical response for a series RLC network connected in shunt with the 50Ω system. By extracting the depth of the notch in transmission response (A_{min}) and the two +3 dB frequencies from the notch (f_l and f_u), the RLC element values can be obtained. The three element values for C_j, R_s, and L_p can be obtained from [1]

$$R_s = \frac{Z_o}{2(\sqrt{L}-1)}$$

$$C_j = \frac{(f_h - f_l)(\sqrt{L}-1)\sqrt{1-\frac{2}{L}}}{Z_o \pi \, f_h f_l}$$

$$L_p = \frac{1}{4\pi^2 f_h f_l C_j}$$

where

$$L = 10^{\frac{A_{min}}{10}}$$

Z_o=50Ω, and C_j, R_s, and L_p are in farads, ohms, and henries, f_l, f_u, and A_{min} are in hertz and decibels.

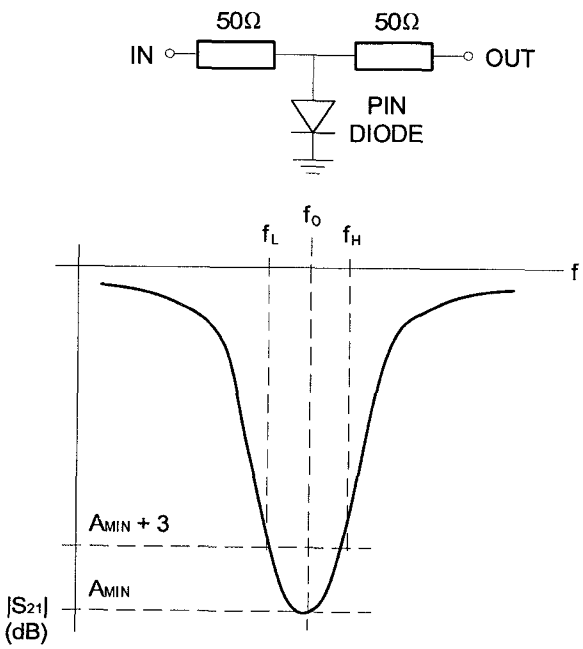

Figure 2. Shunt PIN diode connection and simulated response.

Once the three principle elements have been extracted, the remaining element C_p needs to be determined. This element can be extracted by comparing the small signal model for the RLC resonance with the measured s-parameters connected in shunt. There will be a small skew to the measured resonance due to C_p. C_p can be added to the simulation and its value adjusted until the two transmission responses coincide. R_j is generally very large and does not have a significant effect on the output impedance.

The above procedure was performed on a Lasertron QDE-075C back-illuminated InGaAs/InP photodiode. This diode has a 75 µm wide active area and operates through 10 GHz. This diode was fixtured and measured on an HP8510C analyzer at a variety of reverse biases through 15V. The extraction procedure for C_j, R_s, and L_p outlined above was followed for each bias and results tabulated. Figure 3 shows a graph of these results. C_j and R_s exhibit the expected bias dependence while L_p remains fixed. Fitting the modeled transmission response to the simulations yielded a value of 0.06 pF for C_p. Ultra-low frequency measurements of the diode were made on an HP4275A LCR meter to determine the junction resistance R_j. The results showed this resistance to be greater than 1 MΩ, as one would expect from a reversed biased diode junction. The resulting small-signal model was then compared with the measured, de-embedded s-parameters. The two models fit quite well over the frequency range of 2-10 GHz as shown in Figure 4.

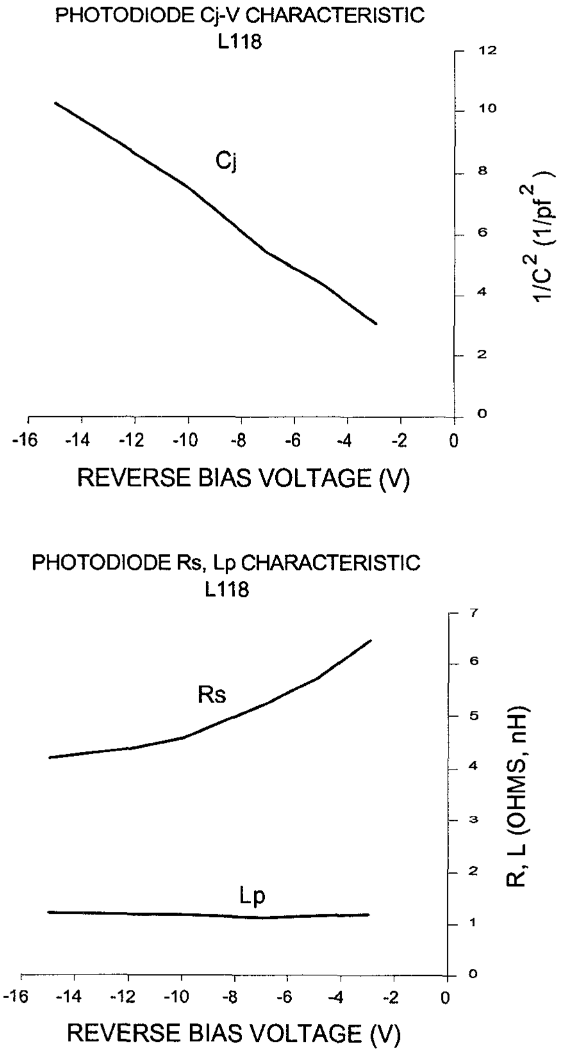

Figure 3. Photodiode C_j, R_s, and L_p bias dependence.

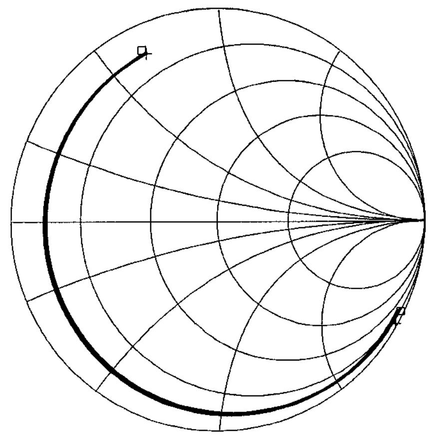

Figure 4. Lasertron QDE-075C RF impedance, measured and modeled.

MATCHING STRUCTURE

The bandpass matching structure chosen for this design was first proposed by Matthaei in 1964 [2]. This structure is similar to that which we have previously used in successfully matching laser diodes at microwave frequencies. [3] [4] Chebyshev impedance transforming networks employ low-pass elements designed to provide a pseudo-bandpass response. The low-pass topology of these networks provide 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 element distributed network at low microwave frequencies.

The circuit element values of a Chebyshev low-pass impedance transforming network can be designed using the tables of normalized element values provided in Reference [2]. In our particular designs, matching resistances of 150Ω and 250Ω were chosen for R_M. These photodiode matching structures were designed to match from R_M to 50Ω over the 2-4 GHz band. To achieve this performance, a fractional bandwidth w=0.8 and transformation ratios of r=3 and r=5 were chosen and the normalized element values read from the tables.

The microwave filters were designed by scaling the normalized elements to 50Ω and f_o=3 GHz. The resulting element values for the 150Ω network are Rs=50Ω, L1=2.96nH, C1=0.766pF, L2=5.74nH, C2=0.395pF, and Rl=150Ω. An analysis of this ideal network yields approximately 0.14 dB in-band insertion loss, which corresponds to a 1.45 maximum in-band VSWR. Similarly, the resulting element values for the 250Ω network are Rs=50Ω, L1=3.83nH, C1=0.649pF, L2=8.11nH, C2=0.306pF, and Rl=250Ω. This ideal network yields approximately 0.35 dB in-band insertion loss, which corresponds to a 1.8 maximum in-band VSWR. Using the two-port detector model, the filter element values were re-optimized to account for the diode parasitics as much as possible. The inductors in the 150Ω network were converted to distributed transmission lines to improve producibility. The resulting matching circuits are shown in Figure 5.

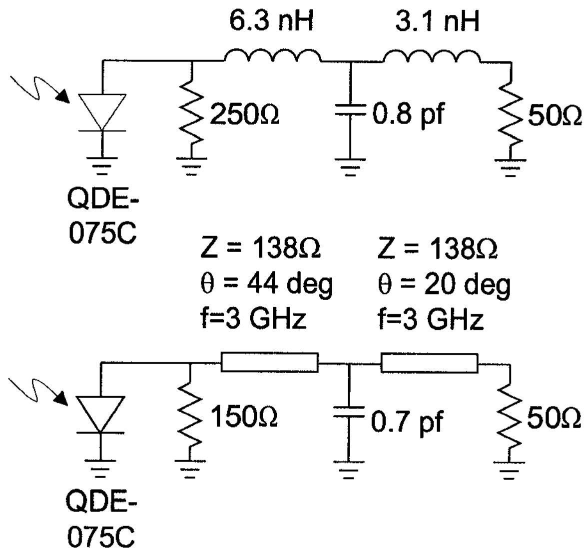

Figure 5. Final photodiode 150Ω and 250Ω matching structures.

CONSTRUCTION

When integrating the detector matching circuit, it is imperative that the detector diode and matching structure be positioned as close together as possible. Eliminating unnecessary line length prevents the impedance of the detector diode from being changed through rotation around the Smith Chart. It is also of tantamount importance to reduce stray capacitance as much as possible. Even a small amount of capacitance is enough the swamp out the high resistance of the matching resistor and degrade the output match.

These circuits were prototyped using a thin-film resistors, chip capacitors, and either transmission line or wire-wound inductors. The inductors were fine-tuned to their correct values by measuring the input impedance of the networks on a vector network analyzer. Afterwards, the photodiode submount was connected and the resulting performance measured.

RESULTS

Figure 6 presents the measured VSWR performance for the Lasertron QDE-075C photodiode taken on an HP8757 scalar network analyzer. For the 150Ω network, a maximum 1.6 VSWR was achieved. With the 250Ω network, a maximum 2.1 VSWR was achieved over the band of interest. This compares well with simulated results of 1.45 and 2.0 VSWRs for the 150Ω and 250Ω circuits, respectively.

Beyond the output match, there is a significant improvement in the transmission response of the link due to the resistive/reactive photodiode matching. Transmission measurements were made of the link insertion loss on an HP8510 network analyzer using both 50Ω resistive matching and the combination resistive/reactive matching of the photodiode. Figure 7 shows the difference in these two responses, i.e. the improvement in insertion gain for both networks. Over the 2-4 GHz band, there is a 6 dB improvement in insertion loss for the 250Ω network, and a 4 dB improvement for the 150Ω network. This is believed to be the first actual demonstration of broadband passive reactive detector matching improvement reported in the literature. Both of these increases in insertion performance correlate well with the theoretical 6.9 dB and 4.7 dB improvements possible for 250Ω and 150Ω resistive/reactive matching in a 50Ω system. Subsequent networks and detectors have been integrated with similar results.

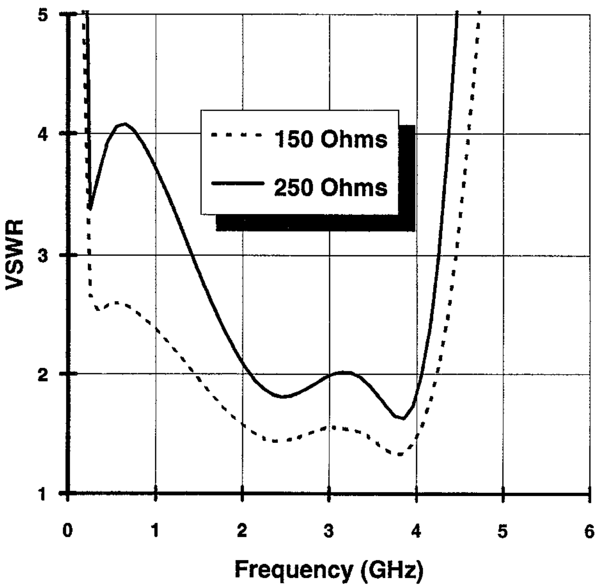

Figure 6. Measured VSWR for resistive/reactive matched photodiodes.

CONCLUSION

We have successfully demonstrated broadband microwave matching of a high speed photodiode. An accurate two-port model was constructed to model the impedance and transmission properties of the detector. This model was used in the successful design of four-element pseudo-bandpass networks to match from 150Ω and 250Ω matching resistances down to 50Ω. The 150Ω network was integrated with a commercially available high speed photodiode to achieve better than 1.6 VSWR across an octave bandwidth, with an associated 4 dB improvement in link insertion loss and sensitivity. A 250Ω matching network similarly achieved better than 2.1 VSWRs across the 2-4 GHz band with a 6 dB improvement in link insertion loss and sensitivity.

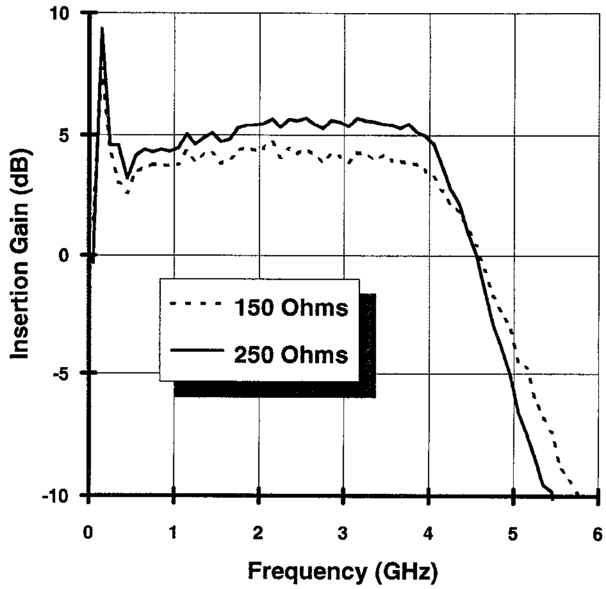

Figure 7. Measured fiber link insertion loss improvement with resistive/reactive matching.

ACKNOWLEDGEMENTS

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REFERENCES

[1] B.C. DeLoach, "A New Microwave Measurement Technique to Characterize Diodes and an 800-Gc Cutoff Frequency Varactor at Zero Volts Bias," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-12, pp. 15-20, January 1964.

[2] G.L. Matthaei, "Tables of Chebyshev Impedance-Transforming Networks of Low-Pass Filter Form," *Proceedings of the IEEE*, Vol. 52 No. 8, pp. 939-963, August 1964.

[3] B. Kanack and C. Goldsmith, "Modelling and matching of directly modulated diode lasers for phased array radar applications," SPIE Conference on *Microwave and Phased Array Processing*, Paper #1703-44, Orlando, Florida, April 1992.

[4] C. Goldsmith and B. Kanack, "Broadband Reactive Matching of High Speed Directly-Modulated Laser Diodes," submitted for publication to *IEEE Microwave and Guided Wave Letters*.