

mA, $V_{ce} = 1.5\text{--}3.5$ V) and from 0.5 to 25.5 GHz. Simulated data calculated with the HBT model¹ variant showed good fits to measurements. Such fits were superior to those obtained with an SGPM developed for the same device. These results manifest the superiority of the HBT model¹ model compared to the SGPM.

Large-signal data were also employed to further validate the extracted models. The HBT's were measured at 840 MHz under four different load/source impedances and continuous wave (CW) excitation using a passive load-pull setup. The quiescent bias condition was $I_c = 17$ mA, $V_{ce} = 3$ V. Table II lists the different terminations together with their second and third harmonic impedances. Fig. 4 shows the measured and simulated transducer gain, power-added efficiency, and collector current as a function of the available input power, respectively. A good agreement is observed for all four cases.

V. CONCLUSIONS

In this paper, the base-collector bias dependence of a recently published HBT large-signal model was modified in order to properly reflect the operational characteristics of power HBT's. The minority-charge bias dependence is determined by employing optimization of all transit-time-related model parameters using the effective base-collector capacitance and the cutoff frequency as simultaneous optimization goals. The modified model resulted in good correspondence between measured and simulated small- and large-signal device characteristics.

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REFERENCES

- [1] G. Massobrio and P. Antognetti, *Semiconductor Device Modeling with SPICE*, 2nd ed. New York: McGraw-Hill, 1993, pp. 45–130.
- [2] L. H. Camnitz and N. Moll, "An analysis of the cutoff-frequency behavior of microwave heterostructure bipolar transistors," in *Compound Semiconductor Transistors: Physics and Technology*, S. Tiwari, Ed. Piscataway, NJ: IEEE Press, 1993, pp. 21–46.
- [3] K. Lu, P. A. Perry, and T. J. Brazil, "A new large-signal AlGaAs/GaAs HBT model including self-heating effects, with corresponding parameter extraction procedure," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1433–1445, July 1995.
- [4] Q. M. Zhang, J. Hu, J. Sitch, R. K. Surridge, and J. M. Xu, "A new large-signal HBT model," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2001–2009, Nov. 1996.
- [5] C.-J. Wei, J. C. M. Hwang, W.-J. Ho, and J. A. Higgins, "Large-signal modeling of self-heating, collector transit-time and RF-breakdown effects in power HBT's," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2641–2647, Dec. 1996.
- [6] P. C. Grossman and J. Choma, Jr., "Large signal modeling of HBT's including self-heating and transit time effects," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 449–464, Mar. 1992.
- [7] C. M. Snowden, "Large-signal microwave characterization of Al-GaAs/GaAs HBT's based on a physics-based electrothermal model," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 58–71, Jan. 1997.
- [8] L. H. Camnitz, S. Kofol, Tom Low, and S. Bahl, "Large-signal high frequency model for GaAs HBT's," in *GaAs IC Symp. Dig.*, 1996, pp. 303–306.
- [9] D. R. Pehlke and D. Pavlidis, "Evaluation of the factors determining HBT high-frequency performance by direct analysis of S -parameter data," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 2367–2373, Dec. 1992.

- [10] L. H. Camnitz, S. Kofol, T. Low, and S. R. Bahl, "Using IC-CAP in the development of an accurate large-signal model for GaAs HBT's," *HP Characterization Solutions*, vol. 2, no. 3, pp. 1–2, 8–11, 1997.
- [11] A. Samelis, D. R. Pehlke, and D. Pavlidis, "Volterra series based nonlinear simulation of HBT's using analytically extracted models," *Electron. Lett.*, vol. 30, no. 13, pp. 1098–1100, June 23, 1994.

A Novel Wide-Band Tunable RF Phase Shifter Using a Variable Optical Directional Coupler

K. Ghorbani, A. Mitchell, R. B. Waterhouse, and M. W. Austin

Abstract—We present a novel RF phase-shifter design with a usable bandwidth of 80:1. The design is verified through demonstration of a proof of concept device, consisting of a readily available voltage variable optical coupler fabricated from LiNbO_3 , combined with an optic-fiber delay line. The design is analyzed theoretically and measurement of the device confirms the predicted range of operation. Methods of extension of this range of operation are discussed.

Index Terms—Optical beamforming, optical directional coupler, phase array, true time delay.

I. INTRODUCTION

Phased-array antennas with highly directional steerable beams are becoming key components of many military, navigation, and satellite communication systems. Requirements for these devices to be small, lightweight, immune to electromagnetic interference, and most importantly, very broad band, have led to the development of phasing elements involving photonic components [1]. The use of optical delay lines in photonically controlled phased arrays has been established as a successful means of providing broad-band phasing between the elements [2]–[4]. However, many systems based on this technique require tunable lasers and/or large numbers of optical switches and, hence, incur considerable expense and complexity.

In this paper, we present a novel broadband electronically tunable RF phase-shifter design. The bandwidth of the design is competitive with true-time delay devices, but has the advantage of a continuously tunable phase shift with a single device. This reduces the number of devices and complexity required for antenna phasing and allows for a continuously steerable beam. Our design is verified through the production and demonstration of a proof-of-concept device utilizing readily available photonic components. The scale of the prototype limited operation to below 80 MHz; however, as predicted, multioctave-bandwidth tunable operation is demonstrated.

Section II of this paper describes the operation of the phasing unit and presents a simple theoretical analysis of its behavior. This

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The authors are with the Department of Communication and Electronic Engineering, Royal Melbourne Institute of Technology, Melbourne, Vic. 3000, Australia (e-mail: rwaterhou@rmit.edu.au).

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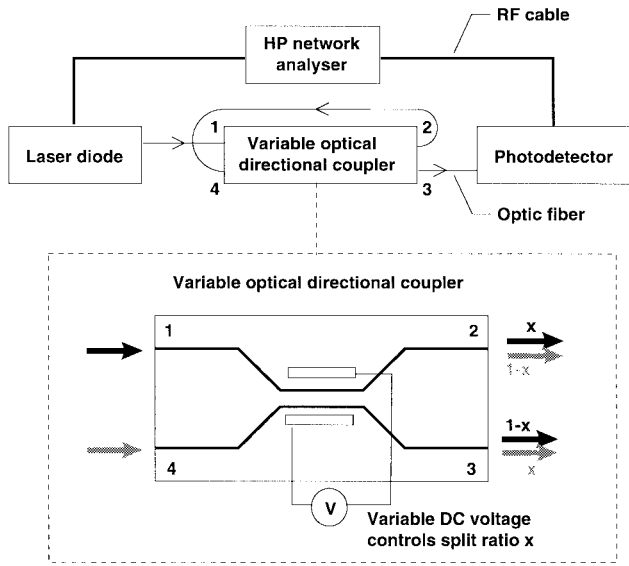


Fig. 1. Experimental setup and schematic of proposed phase shifter.

analysis is then used in Section III to investigate the range of validity of the proposed design. Section IV describes the prototype device and measurements used to verify its behavior. Section V discusses possibilities for development of this device for practical systems application.

II. PRINCIPLE OF OPERATION AND THEORY

The proposed phase-shifter device consists of a variable optical directional coupler and an optical delay line, as shown in Fig. 1. The delay line provides feedback from Ports 2 to 4, while Ports 1 and 3 are connected to a laser diode and photo diode, respectively. The RF signal applied to the laser diode modulates the optical carrier, which is launched into Port 1 of the coupler. The coupler then splits the signal into the ratio $x:(1-x)$ for Port2:Port3, where x is in range 0–1 and is variable depending on the dc voltage applied to the coupler. The split signal at Port 2 then enters the delay line and is then reintroduced to the coupler at Port 4. It is then further split in the ratio $(1-x):x$. A portion proceeds to Port 3 and the remainder reenters the delay line. The total output resulting at Port 3 is a series of attenuated, delayed versions of the input at Port 1. This then proceeds to the photodetector, where it is converted back to an RF signal.

The detected RF signal can be expressed as

$$E_{\text{out}} = E_{\text{in}} \left[(1-x) + x^2 e^{j(\phi)} + x^2(1-x) e^{j(2\phi)} + x^2(1-x)^2 e^{j(3\phi)} + \dots \right] \quad (1)$$

which reduces to

$$E_{\text{out}} = E_{\text{in}} \left[(1-x) + \frac{x^2 e^{j(\phi)}}{1 - (1-x)e^{j\phi}} \right] \quad (2)$$

where $\phi = 2\pi fnL/c$ is the phase shift due to the delay line, f is the RF frequency, n is the propagation constant of the delay line, L is the length of the delay line, and c is the speed of light.

From (2), it is evident that the output will be a scaled and phase-shifted version of the original input signal. For the extreme cases when $x = 0$, $E_{\text{out}} = E_{\text{in}}$, and when $x = 1$, $E_{\text{out}} = e^{j\phi} E_{\text{in}}$. As x is varied from 0 to 1, by applying a dc voltage to the coupler, the phase shift of the detected RF signal will vary, continuously, from 0 to ϕ .

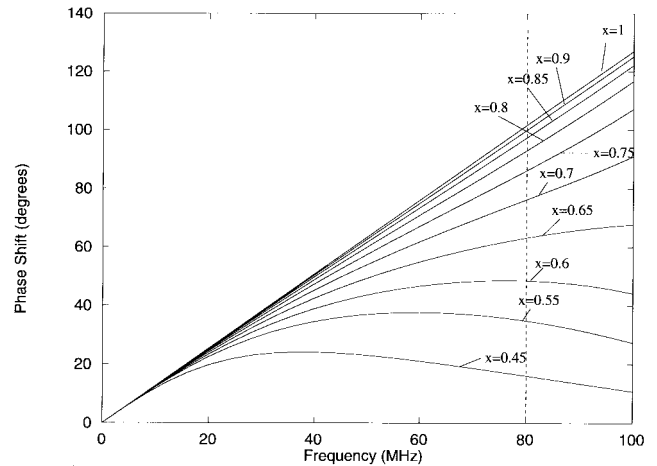


Fig. 2. Theoretical phase shift of output signal as a function of coupling ratio x and operating frequency for delay line of 73 cm with optical losses neglected.

III. ANALYSIS AND RANGE OF VALIDITY

In order for phased-array antennas to maintain a beam angle over a broad range of frequencies, they require phase-shifting components with phase that scales linearly with frequency. Phase shifters with these characteristics based on the true time-delay technique [3] have been demonstrated. However, to achieve continuous beam steering, this phase shift must be tunable, while maintaining its linearity over the frequency range of interest.

Thus, for our device to meet these requirements, it must be able to produce a reasonable phase shift that scales linearly with frequency and can be tuned over a reasonable range of phase shifts while maintaining this linearity. Devices with phase shifts ranging from 0° to 400° , with 6° error, and a signal loss of 28 dB have been reported [5]. These values will be used as a guide for a practical analysis of our device.

To investigate the range over which the device may operate, it is necessary to examine (2). The delay ϕ in (2) was set as 180° at 140 MHz to model the delay incurred by the fiber delay line used in the proof-of-concept demonstration to be introduced in Section IV. Fig. 2 shows the phase shift resulting from (2) as a function of RF frequency for many different coupling ratios (x). It is evident that, within the frequency range of 0–80 MHz, the relationship between phase shift and frequency quickly changes from very linear at $x = 1$ (101° at 80 MHz), to visibly nonlinear at $x = 0.65$ (63° at 80 MHz).

To analyze this relationship more quantitatively, a least squares line fit [7] was applied to each curve. The phase was then taken to be that of the fitted line, with the largest departure of the curve from this line taken as the phase error. From this, it was found that $x = 0.7$ produced a maximum phase error of 6° and all splitting ratios below this produced unacceptably high phase errors, with the exception of the $x = 0$ line, which produces 0° phase shift irrespective of frequency. If the frequency range is reduced, however, the range of usable splitting ratios is increased. Conversely, if a larger frequency range is desired, the range of usable splitting ratios is reduced and, hence, there is a tradeoff between tunability within a specified phase error and bandwidth.

Fig. 3 shows the theoretical attenuation of the RF signal resulting from (2) as a function of RF frequency and coupling ratio (x). It is evident that as the frequency approaches the resonance, the RF attenuation increases rapidly. Below about 80 MHz, however, the attenuation can be seen to vary over only about 4.5 dB, which is an acceptable level for practical operation and allows for several devices to be cascaded to provide larger phase shifts.

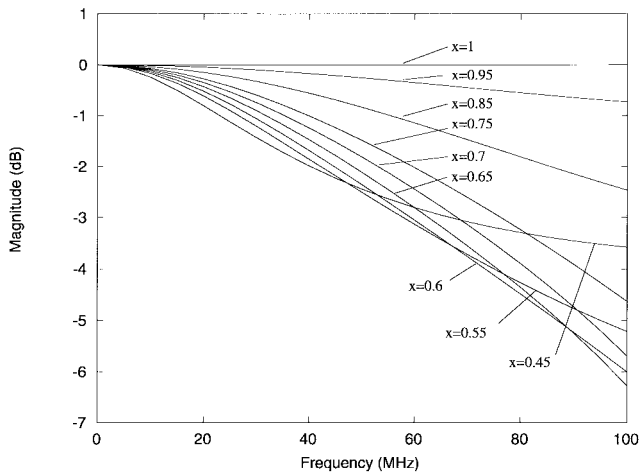


Fig. 3. Theoretical magnitude of output signal as function of coupling ratio x and operating frequency for delay line of 73 cm with optical losses neglected.

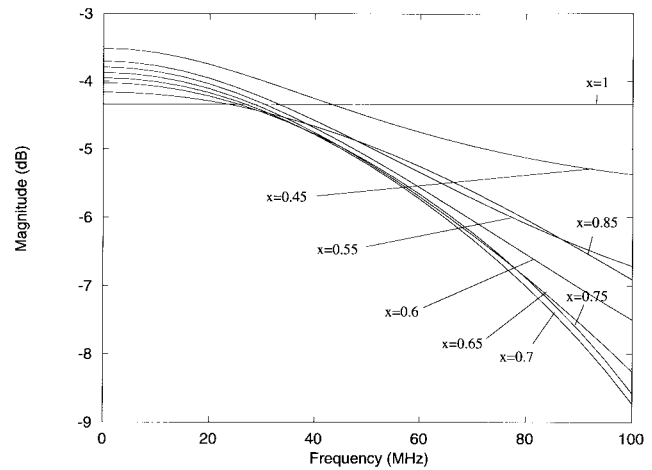


Fig. 5. Theoretical attenuation of the RF signal as function of operating frequency for various coupling ratios (x) with 0.5-dB optical loss at each port of the optical coupler.

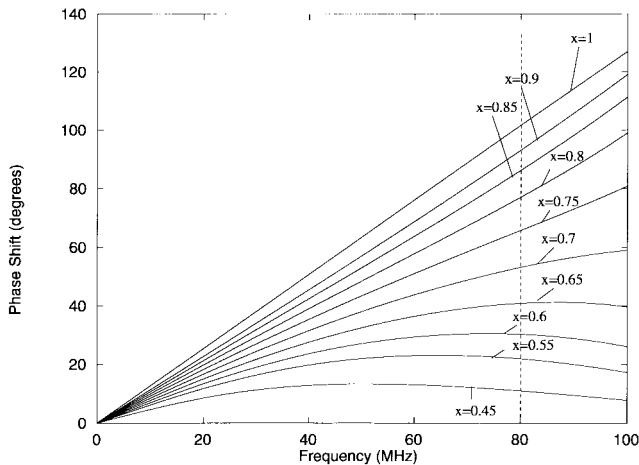


Fig. 4. Theoretical phase shift of output signal as function of operating frequency for various coupling ratios (x) with 0.5-dB optical loss at each port of the optical coupler.

In any practical coupler, there will be losses associated with reflections and scattering at the fiber waveguide interfaces. To model these losses, we introduced a 0.5-dB reduction in optical power at each of the four ports of the coupler in (2). Fig. 4 depicts the phase shift as a function of frequency for this modified equation. It is clear that linearity has been improved due to the introduction of the loss and, hence, the broadening of the resonance. Using the least squares line fit method, as described above, it was found that the phase error at $x = 0.7$ (51° at 80 MHz) was 4° . The tunability had improved from 24° to 50° .

This improvement, however, comes at the price of increased overall insertion loss. Fig. 5 shows the RF attenuation with the inclusion of device losses indicating a maximum loss of around 7 dB at 80 MHz. It is worth noting that the variation in device loss has reduced to around 3.5 dB, which again, is an acceptable level for a practical device.

In order to be competitive with the device reported in [5], we would require to cascade four of the above devices to achieve a maximum phase shift of 400° . This would, however, suggest a minimum phase shift of 200° , a peak loss of 28 dB, and a phase error of 16° , which are unacceptable. If instead of tuning all four devices in unison, we tune first from 50° to 100° with a single device, with all other devices set to zero phase shift, the contribution to signal loss and phase error will be due to one device only. If we then set two devices to 50° for a total of 100° and then tune the pair from 100° to 200° , the phase error and

loss will peak at twice the peak value for a single device. We can then set the first shifter to its maximum of 100° , which will have minimal loss and phase error, and then tune a subsequent pair from 100° to 200° for a total of 300° . This can be continued for many devices, incurring loss and phase error that is approximately only twice the peak value for a single device. In this particular case, the loss would be approximately 14 dB and the phase error approximately 8° , which is comparable with the system discussed in [5]. Other configurations are possible, but this will be the topic of further research.

IV. DEMONSTRATION OF PROOF-OF-CONCEPT DEVICE

The proof-of-concept device was constructed from a preexisting Ti diffused LiNbO₃ optical directional coupler [6], and a 73-cm length of single-mode fiber as the optical feedback loop, as depicted in Fig. 1. The length of the feedback loop was limited by the fiber pigtailing technique used, and was measured to produce 180° phase shift at 140 MHz, indicating that the operating frequency should be below this.

The experimental setup used to determine the RF response of the proposed phase shifter is also depicted in Fig. 1. The output port of an HP 4195A vector network analyzer (VNA) directly modulated a 1300-nm laser diode, which was connected to the input of the phase-shifter device. The output of the phase shifter was connected to a photo diode via a short length of fiber and the resulting electrical signal was fed to the input port of the network analyzer.

Initially, the effect of varying the coupling ratio on the phase of a single frequency was investigated. Fig. 6 shows the measured phase shift as a function of voltage applied to the directional coupler at 80 MHz. The splitting ratio is also shown. It is evident that the phase shift may be electronically tuned from 0° to a maximum of 86° in a continuous fashion. The linearity of these various phase shifts with frequency was then investigated for several different coupling ratios. Fig. 7 presents the phase shift observed over the range of frequencies 1–100 MHz for various splitting ratios. The losses and inherent phase shifts of the directional coupler, in isolation, were measured and incorporated into the theory using the S -parameter technique [8]. The lines represent this theoretical result and the points represent the experimental values. It is evident that there is good agreement between theory and practice. A line of best fit was produced for the measured phase shift versus frequency. The maximum deviation of the measured data from this line was 4° , thus verifying sufficient linearity of the device with frequency.

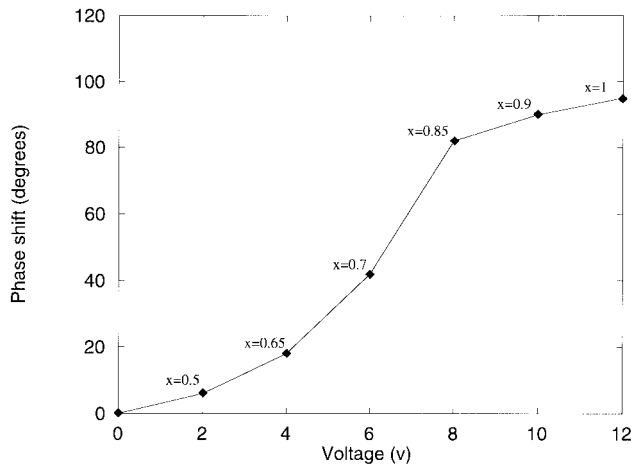


Fig. 6. Measured phased shift of the output signal as a function of applied voltage and, hence, coupling ratio (x) at 80 MHz.

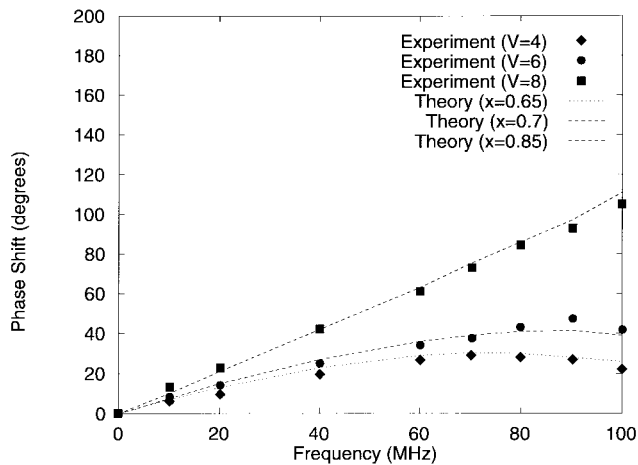


Fig. 7. Measured phase shift as function of frequency and coupling ratio.

V. CONCLUSIONS

A novel broad-band tunable RF phase-shifter design has been presented and verified through the demonstration of a proof-of-concept device. The prototype device achieved a tunable range of phase shifts over the frequency range of 1–80 MHz, with a valid maximum phase shift tunable from 40° to 80° varying linearly with frequency to within 4° . These characteristics are comparable to those reported for more complex and expensive true time-delay techniques. However, our device offers a continuous range of phase shifts, implying that a continuously steerable beam could be achieved for a phased-array antenna.

The low frequency of operation was dictated by the large scale of the proof-of-concept device. The device may be scaled for operation up to several gigahertz, which will be the topic of further research.

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REFERENCES

- [1] M. L. VanBlaricum, "Photonic systems for antenna applications," *IEEE Antenna Propagat. Mag.*, vol. 36, pp. 30–38, May 1994.
- [2] E. J. Murphy, T. F. Adda, W. J. Minford, R. W. Irvin, E. I. Ackerman, and S. B. Adams, "Guided-wave optical time delay network," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 545–547, Apr. 1996.
- [3] W. Ng, A. A. Walston, G. L. Tangonan, J. J. Lee, I. L. Newberg, and N. Bernstein, "The first demonstration of an optically steered microwave phased array antenna using true-time-delay," *J. Lightwave Technol.*, vol. 9, pp. 1124–1131, Sept. 1991.
- [4] Y. Chang, B. Tsap, H. R. Fetterman, D. A. Cohen, A. F. J. Levi, and I. L. Newberg, "Optically controlled serially fed phased-array transmitter," *IEEE Microwave Guided Wave Lett.*, vol. 7, pp. 69–71, Mar. 1997.
- [5] K. Horikawa, I. Ogawa, T. Kitoh, and H. Ogawa, "Photonic integrated beam forming and steering network using switched true-time-delay silica-based waveguide circuits," *IEICE Trans. Electron.*, vol. E79-C, no. 1, pp. 74–79, Jan. 1996.
- [6] J. Katsifolis and M. W. Austin, "Fabrication and modeling of LiNbO_3 directional couplers," in *Proc. 16th Australian Conf. Opt. Fiber Technol.*, Dec. 1991, pp. 64–67.
- [7] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes in C*. Cambridge, U.K.: Cambridge Univ. Press, 1996.
- [8] D. M. Pozar, *Microwave Engineering*. Reading, MA: Addison-Wesley, 1993.

Clarification of a Decoupling Method for Multiconductor Transmission Lines

F. Szidarovszky and O. A. Palusinski

Index Terms—Characteristic impedance, crosstalk, decoupling methods, interconnects, telegrapher equations, transmission lines.

I. INTRODUCTION

Design of printed wire boards (PWB's) for high-speed circuits requires careful analysis of signal transmission problems. Such analysis is based on electrical models of interconnections in the form of transmission lines. Models are simplified to lossless transmission lines because they are relatively easy to analyze and they adequately depict such phenomena as crosstalk or reflections at the terminations. The only parameters that are underestimated by lossless lines are signal delay and dispersion. These effects cannot be adequately analyzed using lossless transmission lines. However, crosstalk and reflections are very important in signal integrity considerations and there are several papers dealing with analyses of multiple-coupled lossless transmission lines. Such analysis involves some intricate aspects of numerical linear algebra, which are not typically known. A paper by Lei *et al.* [2] attempts to describe and systematize the details of such an analysis. However, further modifications yielding very efficient

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