A Low-Cost Approach to Teaching Transmission Line Fundamentals and Impedance Matching

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Abstract:

As part of a NSF-funded Project, Portland Community College has developed a series of low-cost experiments to teach transmission line fundamentals and impedance matching techniques. Using a MFJ-259B SWR Analyzer, experimental exercises to measure reflections coefficients, standing wave ratios, and input impedance have been developed and used in the teaching laboratory. With the addition of a matching unit and simulated load, impedance matching exercises can also be implemented. These laboratory exercises were classroom-tested during Winter Term of 2003 at Portland Community College in a three-credit course entitled MT 240 RF Plasma Systems. This paper describes these experiments.

Introduction

MT 240 RF Plasma Systems is a three quarter-credit course in an associate of applied science degree program at Portland Community College. The course format consists of two lecture-hours per week and three laboratory-hours per week for eleven weeks. Prerequisites for MT 240 include the study of electric circuits, microchip fabrication, and vacuum technology as well as general chemistry, general physics, and college algebra.

The course content includes classroom presentations on plasma physics, transmission line fundamentals, power delivery and impedance matching, and the manufacturing process of sputtering performed at 13.56 MHz. The laboratory portion of the course provides a hands-on application of concepts and principles presented in the classroom, an essential element in training technicians. Laboratory exercises begin with simple plasma physics studies and culminate in sputtering copper onto glass disks in an argon plasma.

Laboratory exercises in basic plasma physics can be implemented using equipment supplied by scientific supply companies, e.g. Fisher Scientific. Using spectrum tubes filled with various gases and a spectrometer, the optical characteristics of plasmas can be studied. A half-coated florescent tube energized by a high-voltage DC source produces the dark spaces, negative glow, and positive column characteristics of DC plasmas. Using a NE-2 neon lamp provides a low-cost means of studying the I-V curve of a neon-based plasma. All of these experiments cost less than $500 per student station.

Laboratory exercises in power transmission at 13.56 MHz begins with the measurement of transmission line parameters, e.g. reflection coefficients, standing wave ratios, and impedance seen at the generator end of the transmission line, e.g. coaxial cable, before progressing to power delivery to a load, $Z_{Load} \neq 50\,\Omega$. A manually-tuned, impedance matching circuit can be inserted prior to the load, and using an impedance meter, it can be shown that the given load can be matched to the output impedance of the RF generator, typically 50 ohms. These experiments will be described in this paper.

The capstone laboratory experience for MT 240 RF Plasma Systems is to sputter copper onto glass disks. For this exercise, a new table-top RF magnetron sputtering systems developed by MKS Instruments, Inc., was used. The system is a manual system and the same techniques developed in preceding experimental exercises are used to operate the MKS Plasma Trainer. This new plasma training system will not be described in this paper, but could be the subject of another paper.

A Low-Cost Impedance Meter

Steve Simons, President of Manitou Systems, Inc., suggested that we look at a MFJ-259B SWR Analyzer distributed by MFJ Enterprises, Inc., and it turned out to be a wonderful suggestion. The MFJ-259B SWR Analyzer is a compact RF Impedance Analyzer. The MFJ-259B combines four basic circuits: a 1.8 – 170 MHz variable-frequency oscillator, a frequency counter, a 50-ohm RF bridge, and an eight-bit microcontroller.

The MFJ-259B makes a wide variety of impedance measurements. Primarily designed for analyzing 50-ohm antenna and transmission line systems, the MFJ-259B measures RF impedance from a few ohms to a maximum of 650 ohms.

The "Main Mode" operating mode includes: Impedance R & X, Coax Loss, Capacitance in pF, Inductance in μH, and Frequency Counter. The "Advanced" operating modes features the following measurements: Impedance (magnitude & phase angle), Return Loss/Reflection Coefficient, Distance to Fault, Resonance, and Transmit Efficiency.

Transmission Line Experiments

Laboratory Activity # 1: Measurement of Reflection Coefficient and Standing Wave Ratio

Materials Needed: MFJ-259B SWR Analyzer, 2 meter length of RG-58 coaxial cable with BNC connectors at each end, and terminations, e.g. 50 ohm, 75 ohm, and 93 ohm.

Pre-Lab Activity: Calculate the reflection coefficient and SWR for a 2-m RG-58 coaxial cable terminated in 75 ohms. Repeat the calculations for a termination of 50 ohms. And finally, repeat the calculations for a terminal of 93 ohms?

Procedure: Set the MFJ-259B to a given frequency, e.g. 10 MHz. Connect the 2-m coaxial cable to the antenna terminal of the MFJ-259B. To the end of the coaxial cable, connect the 75 ohm termination. Using the "Return Loss & Reflection Coefficient" Advanced Menu operating mode, measure the reflection coefficient and SWR. Repeat the measurements for a terminal of 50 ohms and 93 ohms. Finally, compare your measured values to your calculated values.

Sample Experimental Data:

Cable Length	Termination	SWR (Measured)
2 meter	93 Ω	1.8
2 meter	50 Ω	1.0
2 meter	75 Ω	1.5
4 meter	75 Ω	1.5

Measurements made at a frequency of 10 MHz.

Additional investigations: Devise experiments to answer the following questions:

- Is the reflection coefficient a function of the length of the coaxial cable?
- Is the SWR a function of the length of the coaxial cable?
- Is the reflection coefficient a function of signal frequency?
- Is the SWR a function of signal frequency?

Figure 1. Students performing transmission line laboratory exercises using the MFJ-259B SWR Analyzer.

Laboratory Activity # 2: Coaxial Cable as an Impedance Transformer

Materials Needed: MFJ-259B SWR Analyzer, 2-m and 4-m lengths for RG-58 coaxial cable with BNC connectors at each end, two BNC in-line connectors, one 93 ohm termination, and Smith Charts.

Pre-Lab Activity: Using a Smith Chart, predict the impedance at the generator end of a 2-meter length of RG-58 coaxial cable terminated in an open termination and a shorted termination.

Procedure: Connect a 2-meter length of RG-58 coaxial cable terminated in an open termination to the antenna terminals of the MFJ-259B. Measure the impedance using the R&X mode. Compare the measured impedance to the theoretical value obtained using a Smith Chart. Repeat the procedure for a 2-meter length of RG-58 coaxial cable terminated in a short.

Sample Data:

Cable Length	**Termination**	**Measured Z**	**Theoretical Z**
2 meter	Open	R = 0, X = 48 Ω	R = 0, X = 45 Ω
2 meter	Short	R = 0, X = 65 Ω	R = 0, X = 61 Ω

Measurements made at a frequency of 13.56 MHz.

Procedure: Connect a 2-meter length of RG-58 coaxial cable terminated with a 93 ohm resistive load to the antenna terminals of the MFJ-259B. Vary the frequency in 2 MHz increments from 10 MHz to 40 MHz. At each frequency, record the impedance at the source end of the coaxial cable. Plot the impedances on a Smith Chart.

Sample Data:

Frequency in MHz	R in Ohms	X in Ohms
10	30	11
12	29	3
14	30	9
16	35	17
18	44	24
20	60	28
22	79	18
24	89	0
26	79	22
28	59	31
30	44	28
32	35	21
34	30	13
36	29	3
38	30	8

40	35	15

When the data is plotted on a Smith Chart, the locus of points lie on a constant VSWR circle of 1.8.

Impedance Matching Experiment

Laboratory Activity # 3: Impedance Matching Experiment

Materials Needed: MFJ-259B SWR Analyzer, 2-meter RG-58 coaxial cable, matching unit, and load.

Pre-Lab Activity: Impedance matching homework problem.
Determine the L and C component values in a L-type matching circuit to transform a load impedance of 25-j25 Ω into 50-j0 Ω, the cable and generator output impedance.

Procedure: Connect the 2-meter cable to the antenna terminals of the MFJ-259B. Connect the matching unit to the open end of the coaxial cable. Connect the output of the matching unit to the load. Set the operating frequency of MFJ-259B to 13.56 MHz. Alternately adjust the "Tune" and "Load" controls on the matching unit while monitoring the impedance and SWR reading on the MFJ-259B to achieve a matched condition, i.e. SWR equals 1.0 and an impedance of 50-j0 Ω.

Sample Data:

Adjustment	Load	Tune	R in ohms	X in ohms
1	0.797	0.560	12	61
2	0.692	0.560	13	59
3	0.692	0.628	28	55
4	0.591	0.628	32	55
5	0.591	0.714	33	26
6	0.473	0.714	47	21
7	0.473	0.749	36	12
8	0.315	0.749	51	1

When the R and X are normalized and plotted on a Smith Chart, the plotted points move closer and closer to the center of the Smith Chart. This movement toward the center of the Smith Chart indicates that the matching unit is transforming the load impedance into 50 ohms, the characteristic impedance of the RG-58 coaxial cable and output impedance of the generator.

RF Plasma Training System

The capstone laboratory experience is based on a new plasma training system developed by MKS Instruments, Inc., the PPTS-1A Plasma Process Training System. The PPTS-1A consists of a 6-inch ID chamber fabricated from a standard 6-inch ISO cross. The forward horizontal port has an access door and view port. The rear horizontal port has pump connections and tabulation for a 1-torr, full-scale Baratron manometer. The bottom port has mounting hardware for the wafer-substrate platform. The top port has a central Ultratorr-type fitting for the shank of a magnetron sputtering gun and VCR attachments for a Pirani pressure gauge and mass flow controller. The cathode is a four-inch diameter electrode of the magnetron configuration and is powered by a 300-watt Manitou Systems 13.56 MHz RF generator and manual matching unit. See Figure 2.

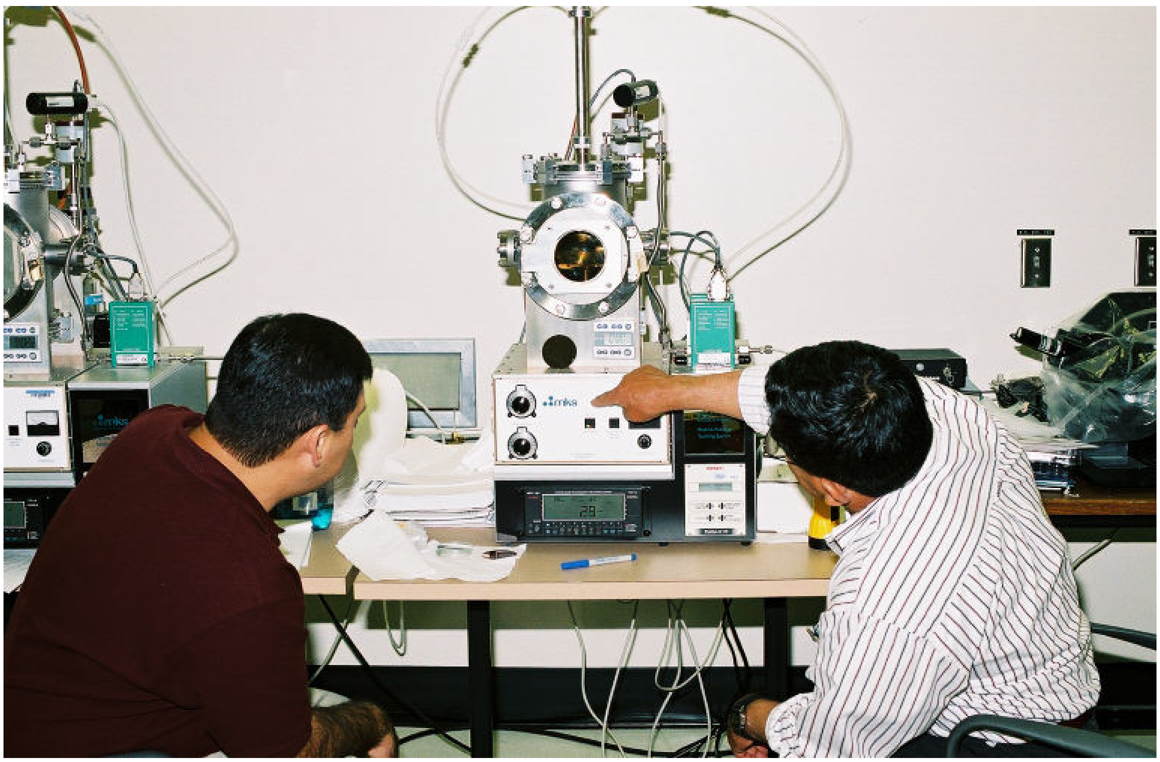

Figure 2. Faculty are being trained on the use of the PPTS-1A Plasma Process Training System.

The advantage of the PPTS-1A Training System is that it is a manually-operated system. Students must pumpdown the chamber, set the pressure by adjusting the gas flow, set the RF power level and match the load impedance to output impedance of the generator. The view port allows them to see the plasma within the chamber while the sputtering process is in progress.

Each student was given two process recipes to run. The process recipes specified a process time, chamber pressure, and power level. After processes their glass disks, each student placed their disk in a display matrix as shown in Figure 3. When all of the disks were processed and placed in the display, students could then view the display and see the effects of changes in pressure, power, and process time on the amount of copper deposited on the glass disks.

Figure 3. Student placing their process disks into a display matrix.

Summary

Using the MFJ-259B SWR Analyzer, low-cost laboratory exercises have been developed to support a technician-level course in plasma-aided manufacturing. The MFJ-259 supports laboratory exercises that focus on transmission line parameters, e.g. SWR and reflection coefficients, as well as more complex impedance matching laboratory exercises. These lab exercises provide an excellent foundation for application in a capstone laboratory exercises using the PPTS-1A Plasma Process Training System.

Bibliographic Information

Hata, D. M. "Instructional Resources for a Technician-Level Plasma Technology Course," Proceedings of the 2003 American Society for Engineering Education Annual Conference & Exposition, June, 2003.

Biographic Information

David M. Hata retired from full-time teaching in June of 2003 after 32 years of teaching at Portland Community College. During his tenure at Portland Community College, he taught in the Electronic Engineering Technology Program for the first 22 years and in the Microelectronics Technology Program for the last ten years. He was awarded one of five Faculty Excellence Awards presented by the PCC Foundation in 1988. His membership in ASEE dates back to 1980. During this time, he has served as chair of the Two-Year College Division and on the Steering Committee for the 1988 ASEE Annual Conference. He has also received two ASEE national awards, the Chester F. Carson Award in 1992 and the Robert G. Quinn Award in 2003.