

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Multiply Resonant EOM

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Abstract

The Laser Interferometer Gravitational-Wave Observatory (LIGO) uses a Michelson interferometer with Fabry-Perot cavities to sense tiny strains associated with gravitational waves. Length sensing and control is achieved through the Pound-Drever-Hall locking technique. For this method of locking, an electro-optic modulator (EOM) is utilized to modulate the phase of laser light, creating frequency sidebands in the beam. In advanced LIGO, there will be three sets of sidebands at modulation frequencies of 11, 29.5 and 55 MHz. Two will be used for length and angle control of the mirrors in the main interferometer (11 and 55 MHz); the other will be used to control the mode cleaner (29.5 MHz). The purpose of this project was to design, build and test a triply-resonant circuit to allow all three modulations to occur inside a single EOM rather than through separate EOMs as is the current procedure. A circuit was designed to have resonance at the necessary frequencies, with roughly equivalent gain and an impedance of 50Ω at each peak. Several iterations of the circuit were built, and the performance of each circuit was evaluated by measuring the transfer function and impedance, and by observing the sidebands using an optical spectrum analyzer.

Contents

1	Background and Motivation	3
2	Circuit Design	4
2.1	Specifications	4
2.2	Initial Design	4
3	Circuit Testing	7
3.1	Initial Surface-Mount Circuit	7
3.2	Flying-Component Circuit	7
3.3	Impedance Measurement	10
3.4	Further Testing	12
4	Future Work	14
5	Summary and Conclusion	14
A	Methods	14
B	Resources	15

1 Background and Motivation

The Laser Interferometer Gravitational-Wave Observatory (LIGO) uses a Michelson interferometer with Fabry-Perot cavities to detect strains induced by gravitational waves. Fabry-Perot cavities use resonance to increase sensitivity to length displacements; to remain at resonance, the cavity length must be an integer multiple of the wavelength of laser light used. To maintain the length for resonance, a feedback system is used; because the intensity will be the same on either side of resonance, modulation of the laser is used to distinguish between situations where the cavity length is too short and too long. This modulation is provided by an electro-optic modulator (EOM) [1, 2].

An EOM is an optical device that modulates the phase, polarization, or amplitude of light according to an electrical voltage signal. The indices of refraction of certain crystals are sensitive to electric fields; this property of a crystal can be exploited to create phase and polarization variations in light passed through the crystal (amplitude modulations are achieved by varying the polarization and passing the light through a polarizer). EOMs can be either resonant or broadband; a resonant EOM contains an LC circuit to create electrical resonance, which means that the input voltage can be much lower than the voltage across the crystal, while a broadband EOM does not contain this component and can be used to generate modulations of a wide range of frequencies. Resonant EOMs can only produce modulations at specific frequencies [3].

In LIGO, the EOM modulates the phase of the laser. Effectively, this phase modulation creates two frequency sidebands in the laser beam: one at the sum of the frequency of the laser light and the frequency of modulation, and one at the difference between them. As the modulated light enters the Fabry-Perot cavity, a certain fraction of the light is reflected; this quantity depends on both the frequency of the incident beam and the length of the optical cavity. Because of this, it is possible to detect length fluctuations in the cavity as fluctuations in the power of the reflected light. Furthermore, through analysis of the relative power of the frequency components of the reflected beam, the direction of length displacement (too short or too long for resonance) can also be determined. To do this, the reflected power signal is mixed with the modulation signal to produce an error signal which is proportional to the displacement from resonance when the cavity is close to resonance. This signal can be used to drive a servo to control the length of the cavity; it is also signal with which gravitational waves could be detected. [1].

In advanced LIGO, two sidebands will be used for length and alignment sensing, and one will be necessary to control the mode cleaner; therefore, three sidebands must be created. This will be achieved by creating an EOM circuit with triple resonance. The goal of this project will be to design, analyze, and test a triply resonant EOM for the advanced-LIGO length-sensing scheme. If successful, by the end of the project, a working prototype of the triply resonant EOM should exist [4].

2 Circuit Design

2.1 Specifications

For functioning in the advanced-LIGO length-sensing scheme, the EOM circuit must meet a few specifications. The circuit must have resonant frequencies of 11 MHz, 29.5 MHz, and 55 MHz, so that the EOM will modulate the phase of the laser at those frequencies. The 29.5 MHz frequency will be used to control the mode cleaner, while the other two will be used for length sensing in the main interferometer. The EOM used will be a New Focus EOM KTP 4064, which has a phase-modulation depth of 13 mrad/V; since the optical modulation depth needs to be around 0.1 rad, the voltage across the EOM will need to be around 8.5 V at the 11 MHz and 55 MHz resonances. Since the available oscillators have a power of 13 dBm, the circuit will need to provide a minimum of 49.6 dB of gain. In addition to this, the impedance at each resonant frequency will need to be 50Ω to avoid signal reflection back into the oscillator. The voltage across the EOM should also be roughly equivalent at 11 MHz and 55 MHz [4].

2.2 Initial Design

The initial design of the circuit is shown in Figure 1. The magnitude and phase of the voltage across the EOM are shown in Figure 2, as well as the impedance across the transformer as seen by the source, and the ratio between the voltage across the EOM and the voltage across the primary ports of the transformer.

As can be observed in these figures, resonance occurs at 11 MHz, 29.5 MHz, and 55 MHz, as specified. The impedance at each resonant peak is around 50Ω (34 dB), and the gain at each is roughly equivalent to the next. The only specification that is not adequately met is the required gain of the circuit. The gain of the circuit is increased by increasing the ratio between the secondary and primary inductances in the transformer; the current circuit uses the highest available value with the appropriate bandwidth. For this reason, it is likely that the gain of this circuit cannot be increased; it will probably be necessary to add another component between the oscillator and the EOM circuit. The current through the primary coil of the transformer is 43-85 mA, and the power dissipated by it is 25-92 mW. The largest power dissipated by a resistor in the circuit (by $R_3 = 32 \Omega$) is 74 mW. These values should not limit the number of circuit components available; they are small enough to make most transformers and resistors possible choices for this circuit.

Generally, this circuit creates the three necessary resonant peaks by creating one resonant peak, and two valleys within it. The inductance in the transformer and the inductor parallel to it, along with the EOM, which acts like a capacitor, and the capacitor in parallel with it, create a resonant peak at around 26 MHz, as shown in Figure 3.

The two inductor-capacitor pairs in parallel with these components create minima at 17 MHz, and 40 MHz, as shown in Figure 4. This occurs because, as the frequency approaches resonance, the impedance of the inductor-capacitor pair drops to zero, causing the voltage across the pair to also drop to zero. Although the voltage across each component is large, the two voltages combine to exactly cancel out. When the effect of these components are combined, the response of the circuit results.

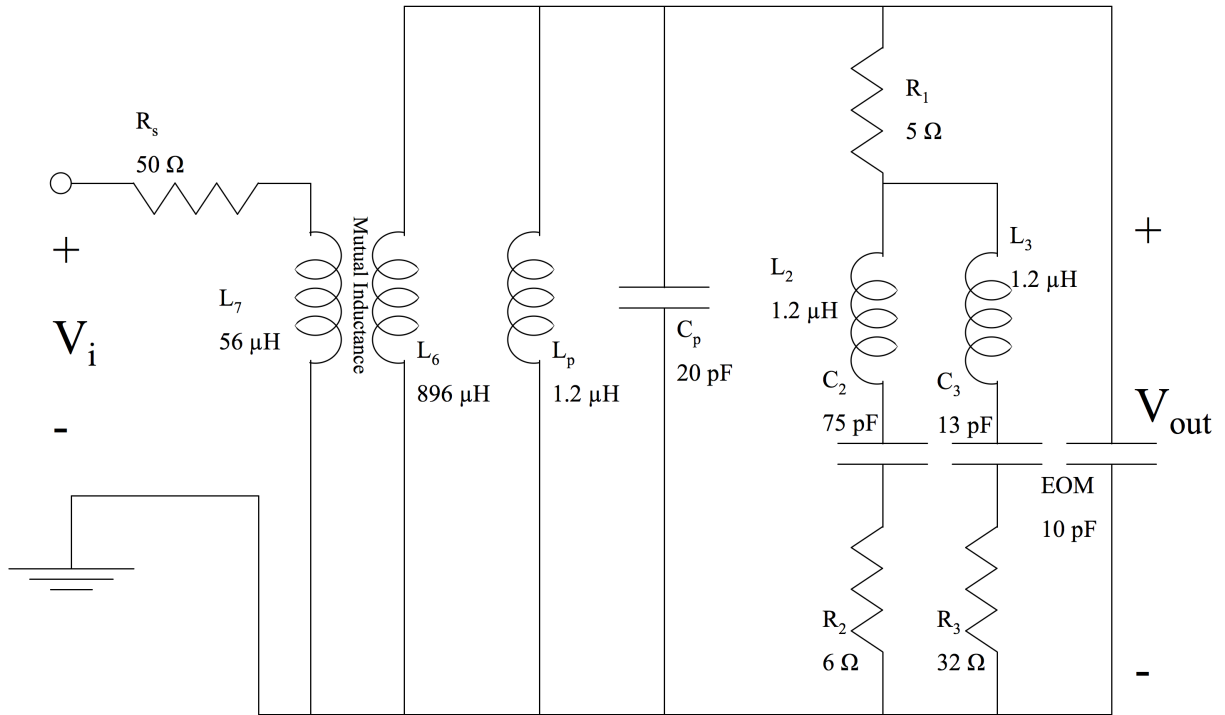


Figure 1: EOM circuit diagram

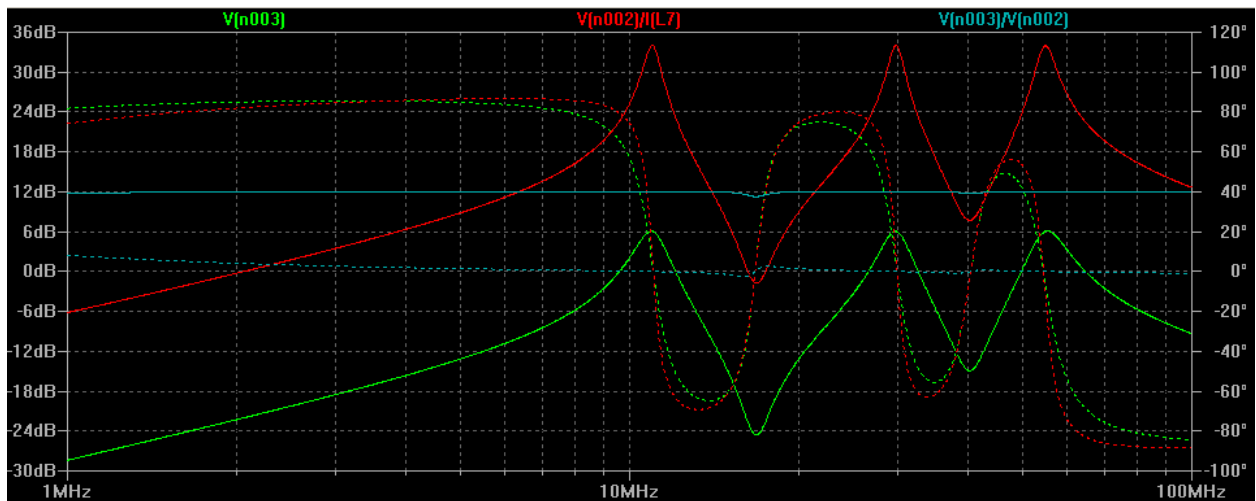


Figure 2: Magnitude (solid) and phase (dashed) of the voltage across the EOM are shown in green, the magnitude and phase of the ratio between the voltage across the EOM and the voltage at the output of the oscillator are shown in blue, and the impedance is shown in red.

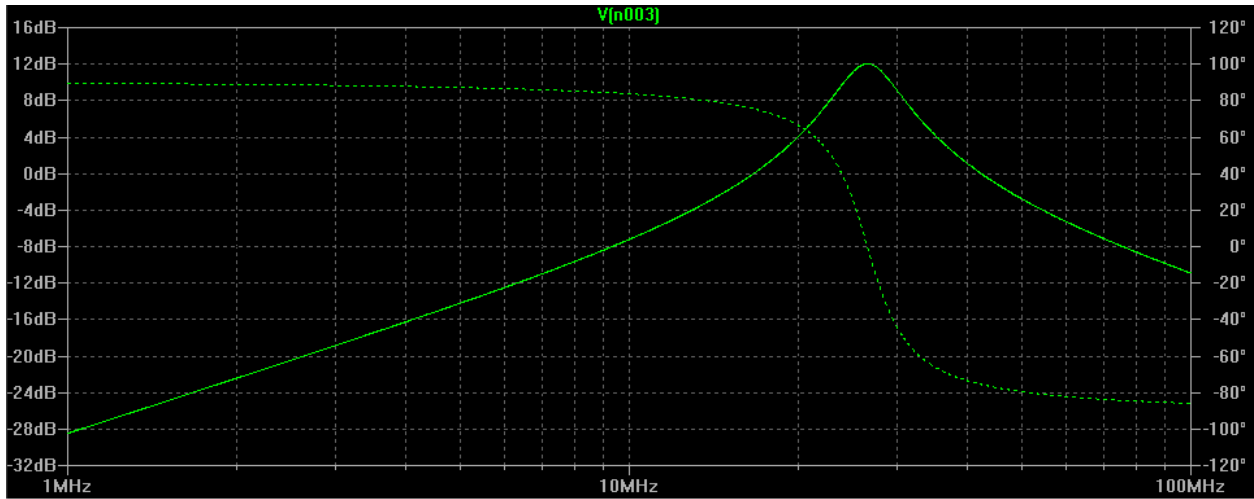


Figure 3: Resonant peak created by just the transformer inductor and the inductor parallel to it, and the EOM and the capacitor in parallel with it.

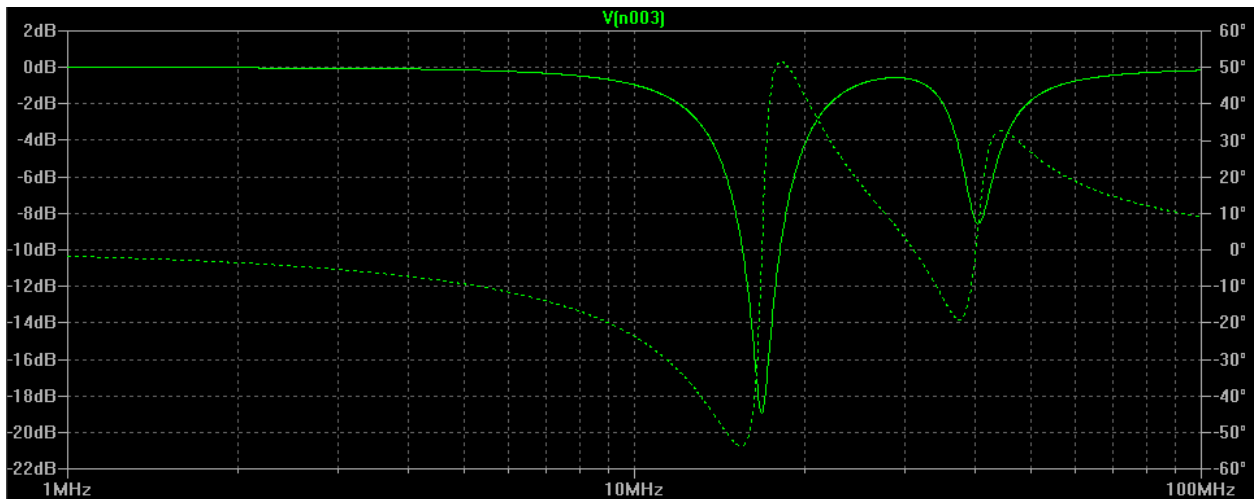


Figure 4: Minima created by the two LC pairs

3 Circuit Testing

3.1 Initial Surface-Mount Circuit

Initially, a circuit was built using surface mount components on a board. A picture of this circuit is shown in Figure 5.

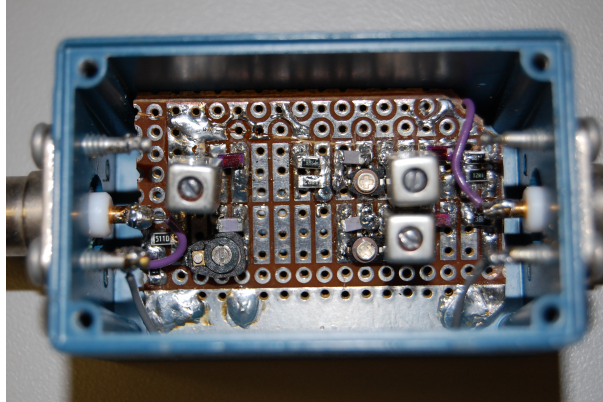


Figure 5: Picture of surface-mount circuit

The transfer function of the circuit was then measured using an Agilent 4395A Network Analyzer. While the transfer function of this initial circuit did not look like the expected transfer function, the discrepancy could be explained to some extent by a short as shown in the circuit diagram in Figure 6. The transfer functions that were measured, simulated as designed, and simulated with a short are shown in Figure 7.

Even if the short is considered, the circuit did not perform as expected; this was likely due to imperfections in the construction of the circuit. One problem was with the construction of the board; for RF circuits, it is necessary to use a special type of board that orients the electrostatic fields in a specific direction.

3.2 Flying-Component Circuit

While flying-component circuits are not ideal for RF applications, it was decided that, since the relevant frequencies are below 100 MHz, a flying-component circuit could be used. This reduces the problems that can occur when using a board and the surface mount components. A flying-component version of the circuit was built according to the circuit diagram in Figure 8. A picture of the circuit is shown in Figure 9.

Next, the transfer function of the circuit was measured; the measured and simulated transfer functions are shown in Figure 10. As can be observed from the figure above, the measured and simulated transfer functions were almost identical.

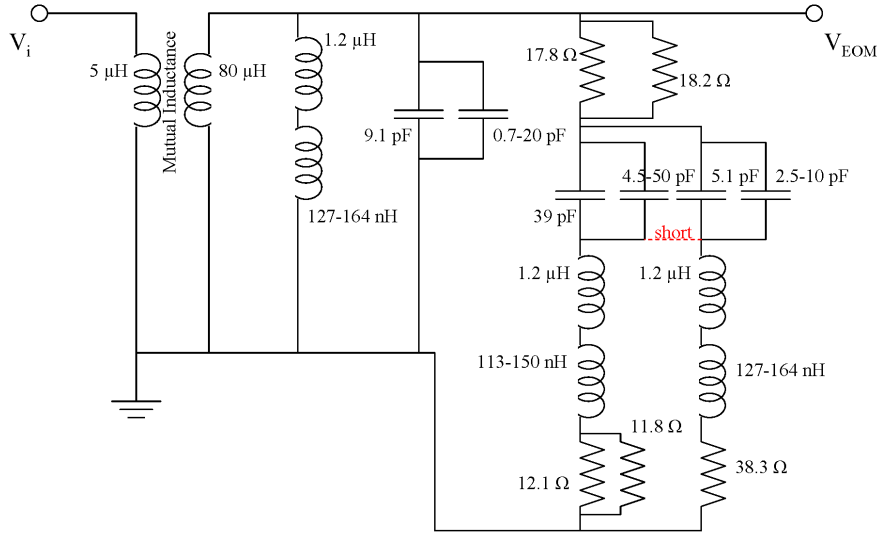


Figure 6: Circuit diagram of surface-mount circuit showing possible short in red

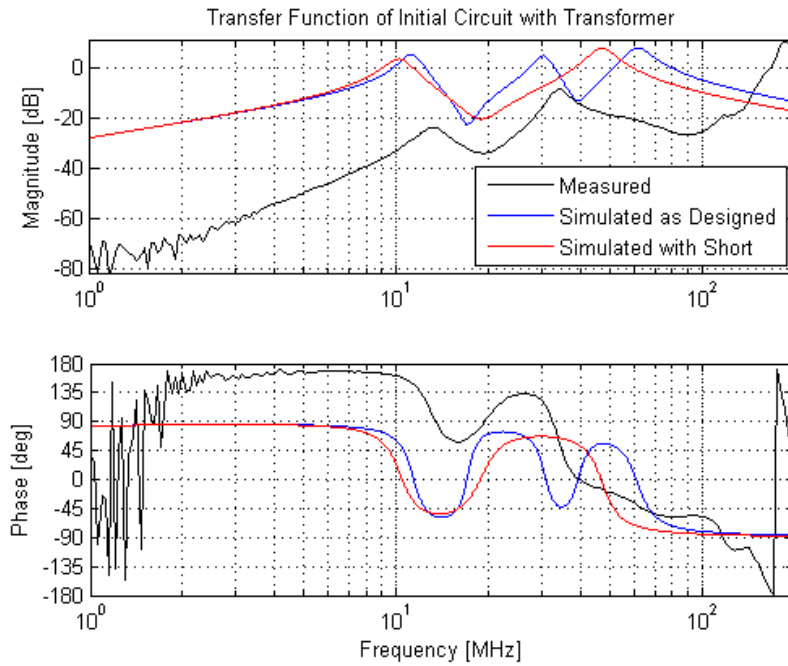


Figure 7: Measured and simulated transfer functions of the surface-mount circuit. Measured is shown in black, simulated in blue, and simulated with short in red.

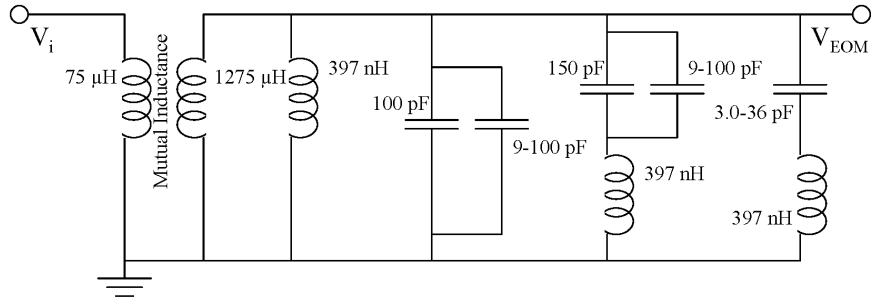


Figure 8: Circuit diagram of flying-component circuit

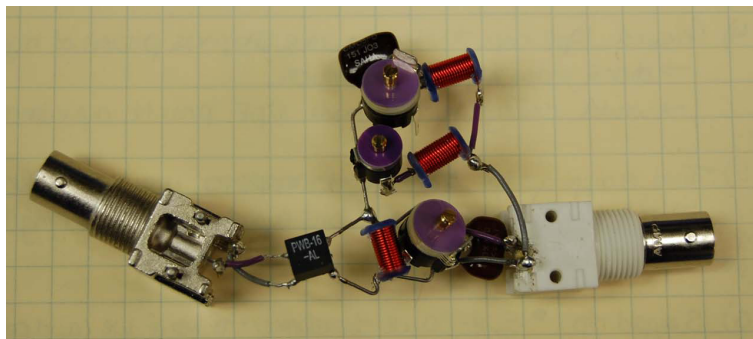


Figure 9: Picture of initial flying-component circuit

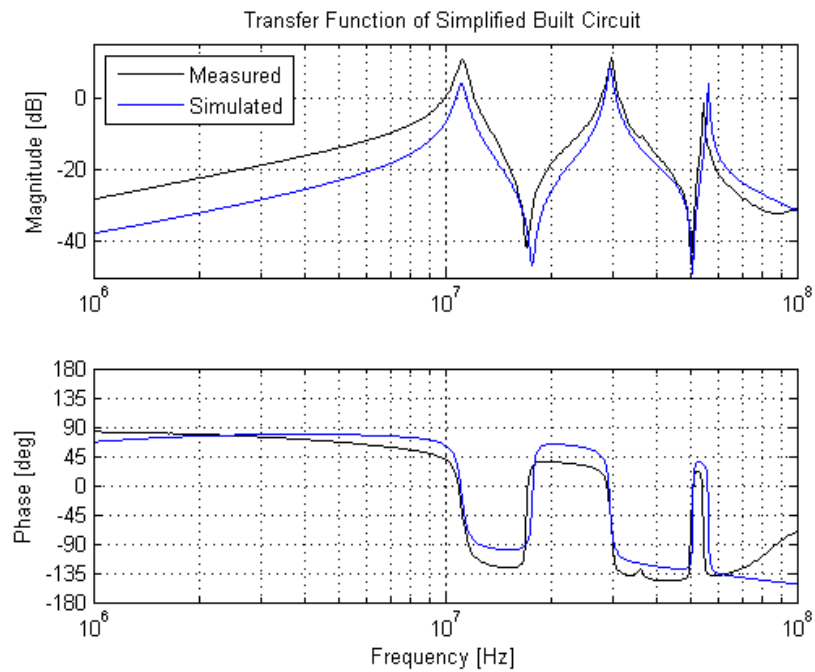


Figure 10: Measured and simulated transfer functions of flying-component circuit

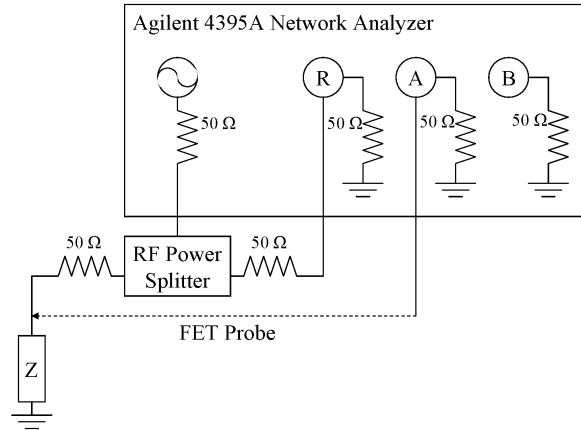


Figure 11: Schematic of impedance testing setup

3.3 Impedance Measurement

Once it was determined that the transfer function of the circuit was functioning properly, it was necessary to measure the input impedance of the circuit to ensure that it was close to $50\ \Omega$ at the resonant peaks to prevent power reflection when the circuit is driven at those frequencies.

An impedance measurement was made using the Agilent 4395A Network Analyzer. This was done by attaching both the A and R ports to the input terminals of the circuit and measuring the transfer function between them. If the network analyzer were ideal, this measurement would simply yield a transfer function of 1 (0 dB) for all frequencies; however, the electrical setup of the analyzer looks more like the diagram shown in Figure 11. For analysis purposes; the power splitter can be treated as a simple node, and the setup simplifies to the following circuit diagram (Figure 12). From this figure, it is possible to calculate that the transfer function is described by the following equation:

$$\frac{V_A}{V_R} = \frac{2Z}{Z + 50} \quad (1)$$

where Z is the impedance of the component being tested. In practice, attenuators must be used to prevent signal reflection back into the power splitter. A diagram of the actual setup is shown in Figure 13.

The system was then calibrated using a $50\text{-}\Omega$ BNC termination, since the transfer function for that impedance should be 1 (0 dB) at all frequencies. Once the system was calibrated, and several impedances were tested to demonstrate that the system was functioning roughly as expected, the impedance of the circuit was measured. The original measurement is shown in Figure 14.

After the original measurement was taken, a capacitor was added to simulate the behavior of the circuit while attached to the EOM. The impedance was then adjusted using resistors until the impedance was at least the same order of magnitude as $50\ \Omega$. Once this was done, the capacitor was removed, and the circuit was attached to the EOM; the impedance of this

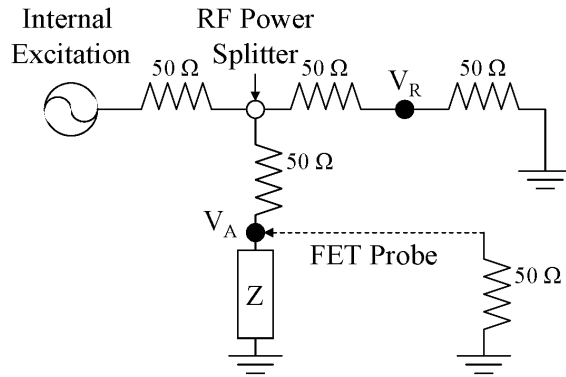


Figure 12: Circuit diagram showing the behavior of the impedance testing setup

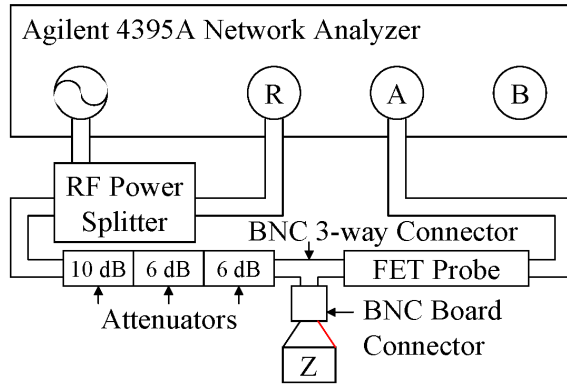


Figure 13: Schematic showing actual setup of Agilent 4395A for impedance testing

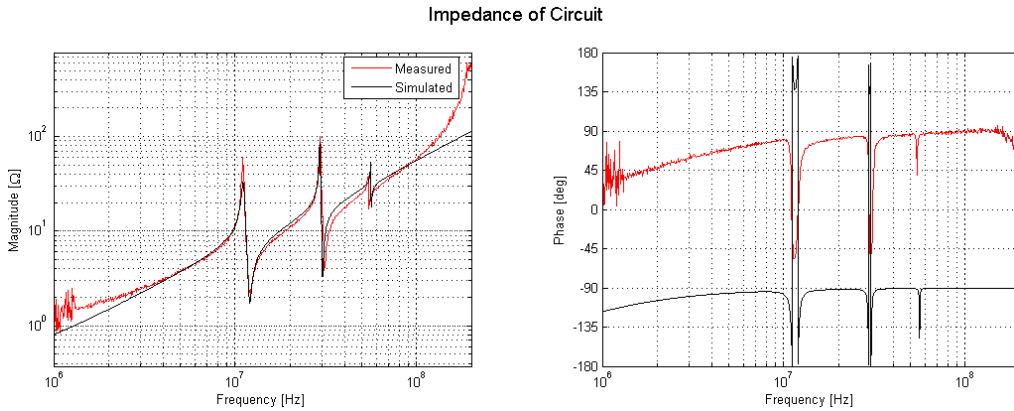


Figure 14: Initial impedance measurement shown with the expected impedance

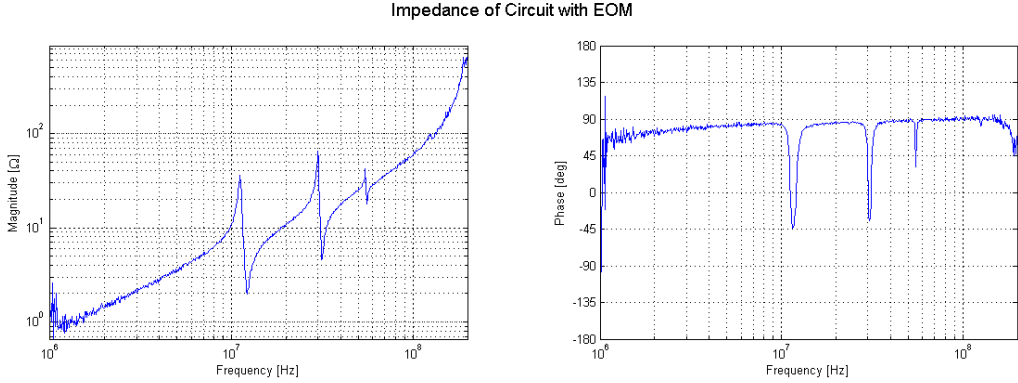


Figure 15: Impedance measurement of circuit attached to EOM

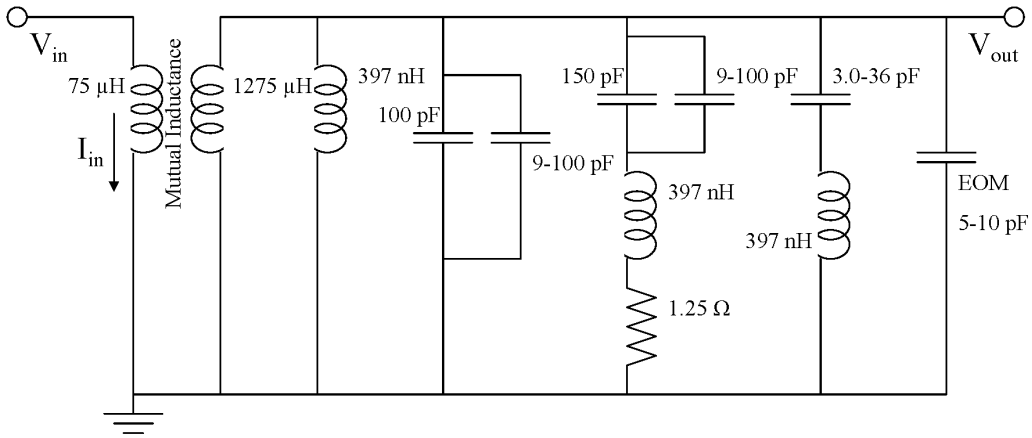


Figure 16: Circuit diagram for final flying-component circuit

new setup was then measured. The final impedance of this circuit is shown in Figure 15. A circuit diagram showing the flying-component circuit attached to the EOM is shown in Figure 16. A picture of the circuit is shown in Figure 17.

3.4 Further Testing

Next, the circuit will be tested using an optical spectrum analyzer. The optical spectrum analyzer contains a scanning Fabry-Perot cavity; when the resonant frequency of the cavity is equal to the frequency of the laser, light is transmitted through the cavity to a photodetector. One of the mirrors is displaced using a piezoelectric mirror spacer driven by an oscillating voltage signal, thereby varying the resonant frequency of the cavity, and the frequency of light transmitted to the photodetector. Through this process, the intensity of light at each frequency can be determined and the spectral makeup of the beam can be analyzed. A diagram illustrating the setup for this test is shown in Figure 18. In addition to the optical spectrum analyzer, a broadband RF detector will also be used to observe and minimize unwanted amplitude modulation.



Figure 17: Picture of flying-component circuit in box attached to EOM

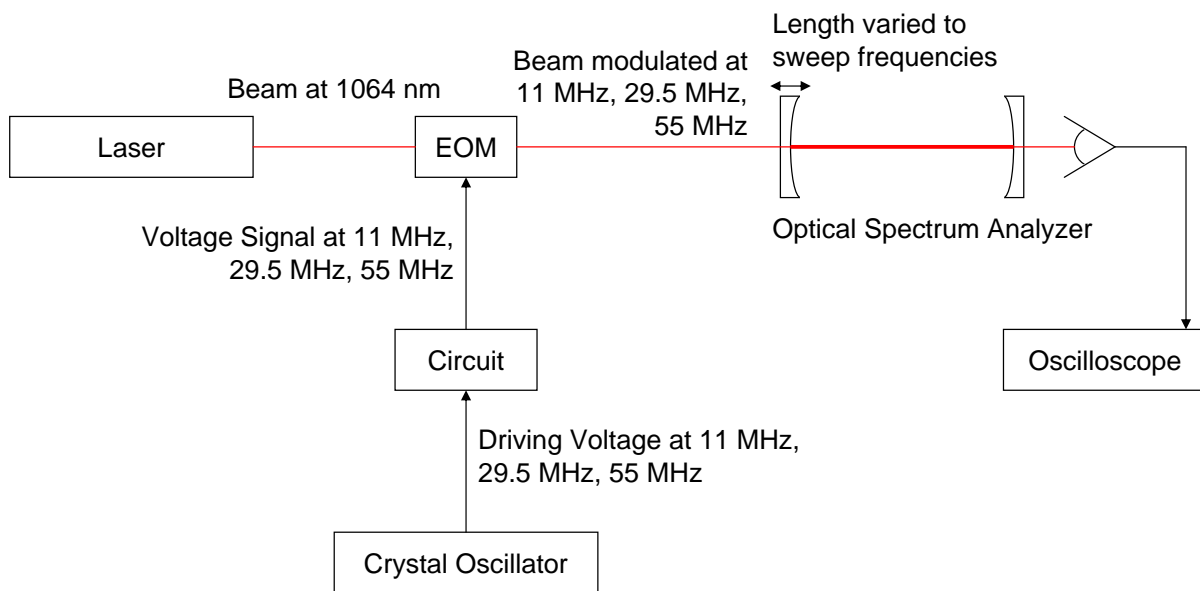


Figure 18: Optical spectrum analyzer setup

4 Future Work

The next step is to observe the modulations produced by the EOM using an optical spectrum analyzer. After that, any necessary modifications to the design will be made, and an improved prototype circuit may be built.

5 Summary and Conclusion

A Methods

B Resources

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