Microwave Analogue to a Subwavelength Plasmon Switch

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Abstract

We construct and characterize a three terminal modulator, which operates in the microwave band at 8.0 GHz (λ = 3.7 cm) via interference of electromagnetic waves confined to a subwavelength structure. On/off ratios of more than 20 dB have been observed.

The modulator consists of intersecting linear arrays of closely spaced metal rods, similar to Yagi antenna aerials, that act as waveguides. The experimental results compare favorably with modeled modulation characteristics determined by full-field electromagnetic simulation. Analogies to potential optical frequency plasmonic devices, consisting of arrays of nanometer-scale metal particles, are discussed.

Introduction

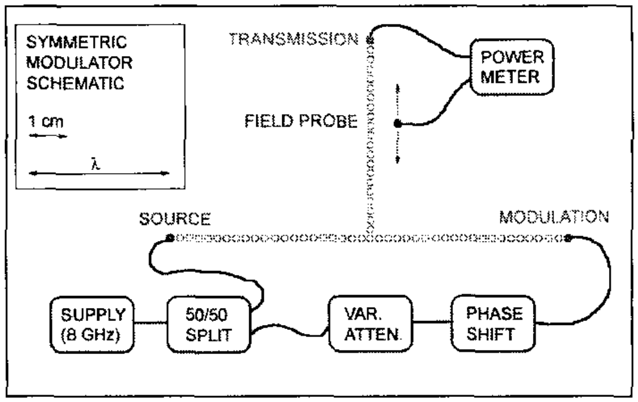
One research direction for development of devices with optical functionality below the diffraction limit of visible light on the scale of several hundreds of nanometers is plasmon waveguide technology. These structures consist of periodic arrays of closely spaced metal nanoparticles, which provide subwavelength confinement and guiding of light via near-field interactions, specifically the collective dipole plasmon oscillations of electrons in neighboring particles[1,2]. Theoretical results have documented the existence of guided modes in plasmon waveguides and furthermore have suggested that light can be routed efficiently around sharp corners. In recent work our group has provided experimental evidence for energy transport in plasmon waveguides[3,4]. However, characterization of functional plasmon devices has so far proven elusive, due in part to the experimental challenges of coupling energy into sub-diffraction limit optical size structures.

In a previous publication, we have discussed the analogy between plasmon waveguides and periodic arrays of centimeter-scale copper rods, similar to Yagi antenna aerials[5]. Yagi antenna arrays also confine electromagnetic energy on a subwavelength scale and support coupled dipole propagating modes. This suggests that one can use the radio frequency laboratory as a testing ground for physical principles relevant to plasmon optics.

Here, we present the characterization of a centimeter-sized interferometric modulator; that is functionally equivalent to a simple subwavelength all-optical plasmon switch, but operates in the microwave regime at 8.0 GHz (λ = 3.7 cm).

Apparatus

The copper rods used to construct our modulator have a diameter of 0.1 cm (0.03 λ) and length 1.4 cm (0.38 λ). They are arranged in linear arrays, spaced equally 0.24 cm (0.06 λ) apart orthogonal to their long axis. The rod arrays are assembled on a platform of Styrofoam that exhibits negligible guiding and small absorption. Our switch design consists of two such linear arrays that meet at right angles to form a "T" structure. Each of the three arms of the "T" consists of 20 rods, not including the single rod at the junction point.



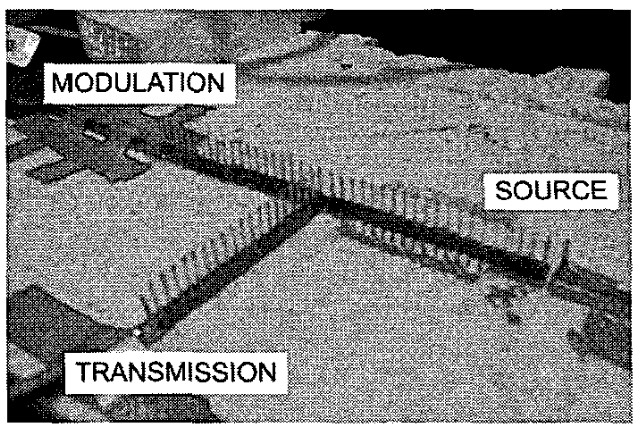


Figure 1: Symmetric Yagi waveguide modulator. Source and modulation signals are generated coherently, but relative attenuation and phase are variable. Power is monitored at the end of the transmission arm, and also can be observed at arbitrary positions via an adjustable probe. Top: Schematic drawing. Bottom: Photograph.

One arm is driven at 8.0 GHz by a center-fed dipole antenna, nominally of the same dimension and spacing as any other rod, but connected to an Agilent 83711B signal generator. This is referred to as the *source* arm. The *gate* (or *modulation*) arm is driven by another dipole antenna coherently from the same generator, but with variable attenuation and phase relative to the signal. A third dipole connected to an Agilent E4419B meter is used to monitor the power at the end of the third arm, which we consider to be the *transmission* terminal of the device. Thus, two possible configurations of this tee – modulator are possible: If the the signal and gate arms are directly opposite one other (at the ends of the "T's" crossbar) we speak of a *symmetric* modulator; if instead the gate forms the stem of the "T" we speak of an *asymmetric* modulator.

When the gate is driven out of phase with the source, the signals combine destructively at the junction and transmitted intensity is expected to lower dramatically. This can be considered the "off" state of the switch. The "on" state can be achieved by changing the gate phase to zero degrees to produce constructive interference, or by attenuating the gate power.

Design Considerations

A discussion regarding relative length scales inherent in the microwave waveguide can help to illustrate a key caveat to the analogy with the plasmonic system.

Experimentally[6] it has long been known that periodic rod arrays only guide electromagnetic waves of free-space wavelength λ if the rod length h is less than $\lambda/2$. It has been shown analytically, using transmission line theory, that this fact is related to the idea that such arrays can be represented as a purely reactive load[7]. From an optical viewpoint, a capacitive load ($h < \lambda/2$) leads to a phase velocity less than the speed of free space propagation c. Correspondingly confinement is observed, much like a region of transparent high-index material in a conventional waveguide system. However an inductive load ($h > \lambda/2$) leads to phase velocity greater than c and lack of confinement.

The antenna engineering literature contains further detailed information on the relationship between rod shape parameters and phase velocity in the slow-wave or capacitive regime[6-8]. To summarize key results, phase velocity decreases as rod spacing decreases, and decreases as rod length increases. Our waveguide arrays consist of relatively long, closely spaced rods. Such a design provides tight confinement in the lateral direction, which best mimics plasmon waveguides and helps minimize radiation loss at sharp corners. Typical Yagi aerials that may be a familiar sight on rooftops or transmission towers are aimed at radiating out electromagnetic energy into the far field and have much wider spacing between elements of typically $\lambda/3$.

Plasmon waveguides, on the other hand, represent a resistive rather than purely reactive load. They operate at the frequency corresponding to the surface plasmon resonance in the constituent nanoparticles. The resonantly enhanced absorption and scattering cross sections of the particles allow for efficient excitation, and enhances coupling between particles[9]. Coupling strength is high even for particle sizes that are small compared to the interparticle spacing and very small relative to the wavelength. In this regime nearest-neighbor coupling interactions can dominate and therefore plasmon waveguides allow for propagation around sharp corners with essentially zero radiation loss in the point-dipole limit. However, their resistive impedance also contributes attenuation to the transmission line. Whereas a reactive load can support in principle an infinitely propagating wave, the high attenuation in plasmon waveguides limits device geometries to the order of a few free space wavelengths.

Demonstration of Concept

A preliminary experiment demonstrates the feasibility of observing interference effects in Yagi waveguides. Here, the transmission arm is removed and power is monitored at a simple right-angle intersection of the gate and source arm. The same amount of power is applied to both gate and source while varying the phase.

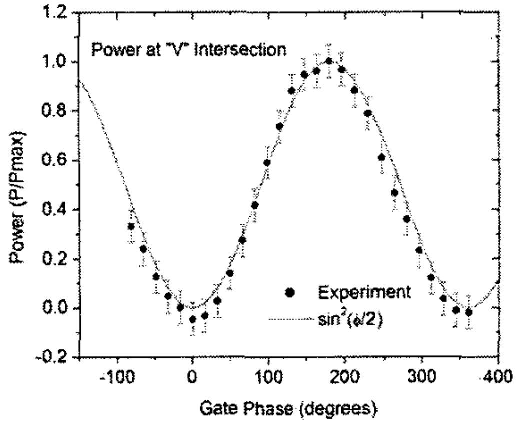


Figure 2: Power observed at the right-angle intersection of two 20-rod Yagi waveguides vs. the relative phase of signal input to the two arms. The solid line indicates the expected functional form.

The solid line in Figure 2 represents the anticipated functional form for interference of two sinusoidal signals of equal amplitude normalized to the maximum power. The measured phase has been adjusted with an additive constant to secure an out-of-phase nulling at zero degrees. Experimental data and theoretical predictions are in good agreement.

Experimental Results

We now consider the three-terminal device, with output power monitored at the transmission port. The effect of varying the gate power as well as phase is recorded.

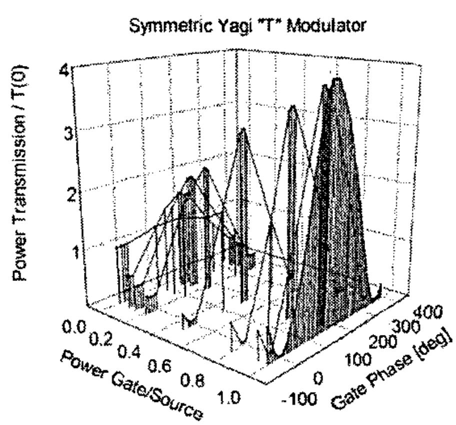


Figure 3: Transmitted power as a function of gate/source power ratio and relative phase in a symmetric Yagi modulator. An arbitrary additive phase is included so that the minimum occurs at zero degrees.

Figure 3 contains the detailed parametric data on the operation of the modulator, in symmetric and asymmetric configurations. At gate/source power ratio of 1 in an ideal interferometer, perfect destructive interference would produce nulls with zero power and perfect constructive interference would produce zones of normalized power of 4, resulting in an infinite on/off power ratio. The performance of the symmetric modulator is indistinguishable from such an ideal device, given empirical error tolerances. This result, while encouraging experimentally, makes it difficult to calculate the maximum on/off ratio of the modulator. Taking the most conservative reasonable error estimate, the ratio is at least 18 dB. However a typical single measurement yields an on/off ratio of 22 to 24 dB.

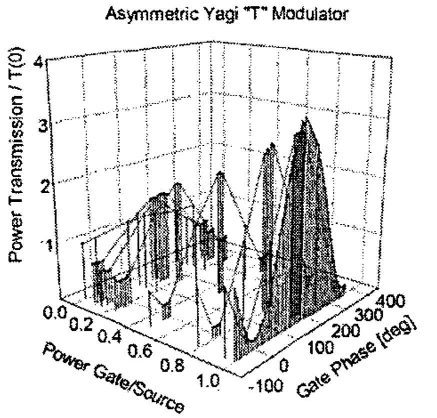


Figure 4: Transmitted power as a function of gate/source power ratio and relative phase in an asymmetric Yagi modulator. An arbitrary additive phase is included so that the minimum occurs at zero degrees.

If the interaction between rods were confined exclusively to first-nearest neighbors, the asymmetric tee would be expected to exhibit nulls and peaks of similar quality to the symmetric case. The experimental result therefore indicates that longer-range interactions, and perhaps higher order modes, play an important role.

Simulation Results

Full-field electromagnetic calculations were performed on the modulator structure using commercial antenna simulation software[10]. Previously we have found excellent agreement between experimental results and simulations of passive Yagi waveguide structures[5].

Figure 5 illustrates the field intensity in region surrounding a simulated asymmetric modulator. In the on state, the source and modulation signals add constructively at the waveguide intersection, and a relatively large amount of power is transmitted. In the off state, out-of-phase source and modulation signals produce a null at the junction and a decrease in transmitted power. As anticipated, power is lost to far field radiation exclusively at waveguide corners and terminations.

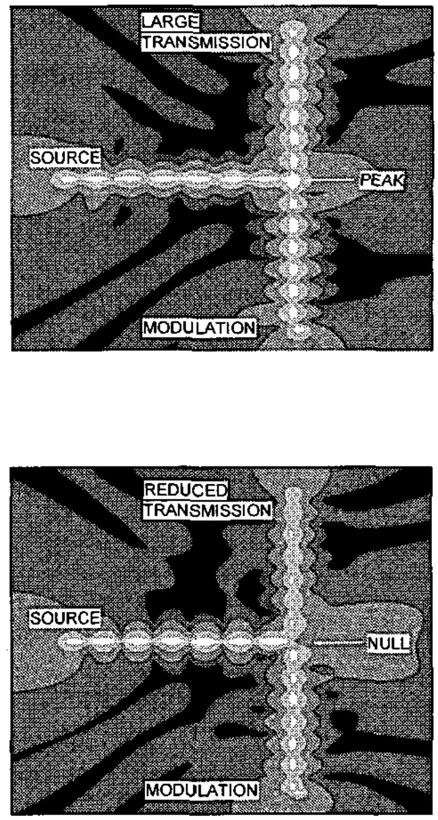


Figure 5: Logarithm of total field intensity in the vicinity of an asymmetric Yagi modulator, as determined by simulation. Total scale is three orders of magnitude. Top: in-phase modulation. Bottom: 180 degrees out-of-phase modulation, which results in a reduction by half of the transmitted power.

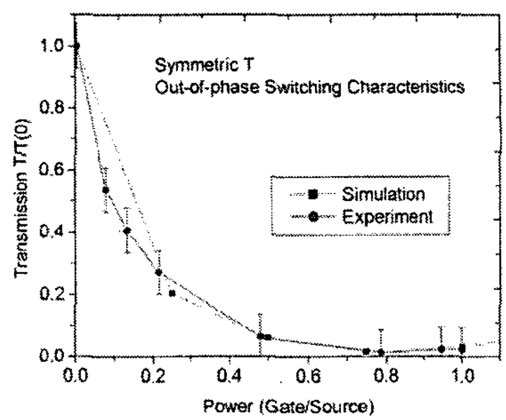


Figure 6: Transmission vs. gate power for symmetric Yagi modulator with gate out of phase; simulation (squares) and experiment (circles).

In Figure 6, we compare quantitatively the transmission characteristics of a simulated symmetric modulator to the experimental data presented in the previous section (Figure 3). The two results are in excellent agreement. In the short term we hope to refine the model of the asymmetric modulator to obtain similar agreement with experiment.

Continued modeling efforts will be geared toward prototyping reflectors, radiation-suppressing elements, enhanced coupling arrays, and other features that promise to prove useful in further design of microwave antenna array devices. In particular we will address the improvement of modulator transfer characteristics and coupling efficiency.

Conclusions

A microwave interferometric modulator consisting of subwavelength antenna waveguides was demonstrated. On/off ratios of over 20 dB can be achieved. When operated in the symmetric configuration, the observed characteristics agree quite well with expectations and with simulated results. We continue to make progress in the more general case.

Acknowledgments

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References

1. M. L. Brongersma, J. W. Hartman, and H. A. Atwater, "Electromagnetic energy transfer and switching in nanoparticle chain arrays below the diffraction limit," *Phys. Rev. B* **62**, R16356 (2000)
2. M. Quinten, A. Leitner, J. R. Krenn, and F. R. Aussenegg, "Electromagnetic energy transport via linear chains of silver nanoparticles," *Opt. Lett.* **23**, 1331 (1998)
3. S. A. Maier, *Thesis*, California Inst. of Tech.
4. S. A. Maier et. al., *Nature Materials* (forthcoming)
5. S. A. Maier, M. L. Brongersma, and H. A. Atwater, "Electromagnetic energy transport along arrays of closely spaced metal rods as an analogue to plasmonic devices," *Appl. Phys. Lett.* **78** (1), 16 (2001)
6. J. O. Spector, "An Investigation of Periodic Rod Structures for Yagi Aerials," *J. IEE* **105**, 38 (1958)
7. D. L. Sengupta, "On the Phase Velocity of Wave Propagation along an Infinite Yagi Structure," *IRE Trans. Antennas Propag.* **AP-7**, 234 (1959)
8. F. Serracchioli and C. A. Levis, "The Calculated Phase Velocity of Long End-Fire Uniform Dipole Arrays." *IRE Trans. Antennas Propag.* **AP-7**, 424 (1959)
9. U. Kreibig and M. Vollmer, Optical Properties of Metal Clusters (Springer-Verlag, Berlin, 1994)
10. EZNEC v. 2.0, R. W. Lewallen (1999)