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INITIAL STUDIES OF REFLECTOMETER FOR ITER

FINAL REPORT

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ITER-related activities taking place over the last year were concentrated primarily on the area of advanced reflectometry systems. In particular, we have concentrated on reflectometer systems for density profile and density fluctuation studies on ITER. This interest has led us to spend much of our time investigating the pulsed radar time-of-flight reflectometer approaches (i.e. moderate pulse and ultrashort pulse). Pulsed radar systems offer the ability to make detailed profile measurements using fixed frequency sources, avoiding the need for highly stable sweepable sources as required by the more traditional FM radar systems.

Moderate Pulse Radar Reflectometry

In moderate pulse radar reflectometry, a wave packet at a given frequency with a moderate pulse duration (0.5-1.0 nsec) propagates into the plasma, reflects, and then propagates back out of the plasma. By performing double-pass time-of-flight measurements on the reflected wave, the distance to the reflecting layer can then be computed (as long as the pulse duration is not so short that the reflection region "covers" an appreciable portion of the profile. Density profile measurements can then be built up from similar time-of-flight measurements obtained at a number of discrete frequencies within the 150-250 GHz frequency range corresponding to X-mode operation on ITER.

High speed switching at millimeter-wave frequencies is traditionally done using a waveguide mounted Schottky diode mixer. Such mixers, however, are extremely lossy (minimum insertion loss of 6-10 dB) and are restricted to a maximum tens of milliwatts of millimeter-wave power. Our approach is to develop quasi-optical beam control arrays, consisting of hundreds of individual diodes, capable of switching hundreds of milliwatts of millimeter-wave power at extremely high speeds. We have now fabricated two such high speed switching arrays. The first array, designed for testing on devices such as DIII-D or TEXT-U, worked well as a broadband switch over the frequency range 40-75 GHz with an insertion loss of 2.8 to 5.7 dB depending on the operating frequency. The second switch, designed for use on ITER, was found to switch relatively well at 117-135 GHz. The poorer than expected performance was a result of a large parasitic capacitance which limited the Schottky varactor diodes to a $C_{\max}/C_{\min}$ ratio of 2-2.5, rather than the 6-7 they were designed for. We are now in the process of obtaining E-H tuners which will allow us to tune the performance of the switches for improved switching at select frequencies.

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During the past year, we have entered into a collaborative effort with Martin Marietta Electronics Systems to fabricate a new generation of beam control arrays. Four complete 2.1"x2.1" wafers have now been fabricated at their MMIC (monolithic Millimeter-wave Integrated Circuits) foundry. We have now completed I-V and C-V testing of these arrays, which exhibit breakdown voltages in the 7-12 V range and diode capacitance $C_{\max}/C_{\min}$ ratios in the 4-7 range. These new arrays will be mounted in a quasi-optical two-grid configuration, in which simulations show they should perform significantly better than the single grid switches fabricated and tested to date, with an insertion loss of less than 1 dB and a contrast ratio (the ratio of the transmitted power in the ON state to that in the OFF state) greater than 40 dB.

Ultrashort Pulse Radar Reflectometry

In ultrashort pulse radar reflectometry, an extremely short pulse (1.5-3.0 psec) is launched into the plasma. This pulse is sufficiently short that it contains Fourier components that extend past the ~250 GHz R-wave cutoff of ITER plasmas. Upon reflection, each component of the incident wavepacket reflects from a different spatial location (density) in the plasma thus spreading out the reflected wave packet in time (up to 50 nsec for ITER). By separating out the different frequency components of the reflected wavepacket, and obtaining time-of-flight measurements for each of the subpackets, the entire density profile may then be determined from a single source and a single set of measurements.

During the period of June 21 through August 19 of this year, we were fortunate to have Aaron Romanowsky, one of the approximately 25 students selected this year by the U.S. Department of Energy, Office of Fusion Energy (OFE) for the National Undergraduate Fellowship Program in Plasma Physics & Fusion Engineering, join our group. He was involved in prototyping and testing an ultrashort pulse radar reflectometer system utilizing the 3 V, 65 psec FWHM pulse generator previously used in our earlier proof-of-principle moderate pulse radar experiments.

The initial proof-of-principle experiments of the ultrashort pulse radar reflectometry diagnostic were performed first in the laboratory, and subsequently on the CCT tokamak at UCLA. Although not ideal for use even on CCT (a shorter pulse duration of 20-30 psec would be preferable), it proved none-the-less sufficient for our initial test purposes. These tests proved highly successful, given the constraints dictated by the small size and relatively low toroidal B-field of CCT with respect to mainstream machines such as DIII-D and future machines such as ITER. A two channel system was set up, to simultaneously monitor the reflected signals from two different positions along the density profile. The temporal resolution of this prototype system was experimentally determined to be ± 200 psec, corresponding to a position uncertainty of ± 3 cm.

On the CCT tokamak, there were significant variations in the reflected wave amplitude, with the largest variations in ohmic discharges and the smallest variations under H-mode conditions. These variations in reflected signal amplitudes are believed to arise solely from the presence of large amplitude fluctuations/turbulence in the immediate area of the plasma reflecting layer. This supposition is strongly supported by observations made during the L-to-H transition regions, in which a similar reduction in shot-to-shot amplitudes was observed. Interestingly enough, the strong variations in reflected signal amplitudes was not accompanied by similar strong variations in reflected signal delay times. Therefore, the accuracy of the diagnostic was not seriously impaired (except in those cases where the amplitude of the reflected signal was insufficient to be distinguished above the background noise levels).

This sensitivity to density fluctuations is somewhat troublesome, as a large dynamic range will be required in order to maintain an acceptable signal-to-noise ratio. On the other hand, there is now some experimental evidence that ultrashort pulse radar reflectometry may be useful as a density fluctuation diagnostic as well as a density profile diagnostic. 1-D numerical simulation programs have been developed to model the moderate pulse and ultrashort pulse radar reflectometry diagnostics under both CCT and ITER-like conditions. By superimposing a random density fluctuations upon the background density profile, we are now beginning to investigate numerically the sensitivity of the diagnostics to various levels of density fluctuations. Preliminary results tend to confirm the large reflected wave amplitude variations seen in the CCT data. These simulation results, as well as our CCT test results, will be presented at the IAEA Technical Meeting on Microwave Reflectometry for Fusion Plasma Diagnostics to be held at Princeton in January. A short paper is also being prepared, which we intend to submit to Review of Scientific Instruments.

On the technology side, we are making good progress in developing the nonlinear transmission lines (NLTLs) which will generate the high power, ultrashort pulses required for this diagnostic. Our simulations indicate that we would require a minimum of 32 W (i.e. 57 V on a 50 Ω line) contained within a ~ 1.5 psec pulse for use on ITER. The high power and short pulse duration requirements of this diagnostic requires an order of magnitude increase in peak voltages over any ultrashort pulse NLTL with comparable pulse durations reported to date. These NLTLs, however, have utilized almost exclusively conventional Schottky diode varactors as the nonlinear elements in the line. Using the multiple quantum barrier varactor devices that were developed in the course of our earlier frequency multiplier studies, we believe that we can generate the requisite combination of power and pulse length with a single NLTL. Higher power levels will be achieved through the quasi-optical power combining of a number of such lines. This concept will soon be tested once the hybrid NLTL arrays (consisting of commercial beam lead diodes placed upon custom Duroid printed circuit boards) currently in fabrication are completed.

Papers and Proceedings Articles

- (1) L.B. Sjogren, H-X.L. Liu, T. Liu, F. Wang, C.W. Domier, and N.C. Luhmann, Jr., "Control Techniques for Millimeter-Wave Active Arrays," published in *International Journal of Infrared and Millimeter Waves*, **14**, pp. 1175-1189, June 1993.
- (2) L.B. Sjogren, H-X.L. Liu, X-H. Qin, F. Wang, C.W. Domier, and N.C. Luhmann, Jr., "Electronic and Electromagnetic Devices for Millimeter-Wave Beam Control Arrays," published in *International Journal of Infrared and Millimeter Waves*, **14**, pp. 1201-1216, June 1993.
- (3) L.B. Sjogren, H-X.L. Liu, X-H. Qin, C.W. Domier, and N.C. Luhmann, Jr., "Array Designs for Amplitude and Phase Control of Millimeter-Wave Beams," published in *International Journal of Infrared and Millimeter Waves*, **14**, pp. 1509-1529, August 1993.
- (4) L.B. Sjogren, H-X. Liu, F. Wang, T. Liu, X-H. Qin, W. Wu, E. Chung, C.W. Domier, and N.C. Luhmann, Jr., "A Monolithic Diode Array Millimeter-Wave Beam Transmittance Controller," published in *Microwave Theory and Techniques*, **41**, pp. 1782-1790, October 1993.

Presentations

- (1) T. Liu, X-H. Qin, F. Wang, L. Sjogren, C.W. Domier, and N.C. Luhmann, "New developments in Millimeter-Wave Beam Control Arrays," presented at the *18th International Conference on Infrared and Millimeter Waves*, Colchester, UK, September 6-10, 1993.
- (2) W-M. Zhang, H. Shi, C.W. Domier, and N.C. Luhmann, "Nonlinear Transmission Lines Using Multiple Barrier Varactor Devices," presented at the *18th International Conference on Infrared and Millimeter Waves*, Colchester, UK, September 6-10, 1993.
- (3) T.Y. Liu, L.B. Sjogren, F. Wang, C.W. Domier and N.C. Luhmann, Jr., "Millimeter-Wave Schottky Diode Beam Control Arrays," presented at the *Asia-Pacific Microwave Conference 1993*, Hsinchu, Taiwan, Oct. 18-21, 1993.
- (4) W-M. Zhang, H. Shi, C.W. Domier and N.C. Luhmann, Jr., "Monolithic Nonlinear Transmission Lines for Short Pulse and Harmonic Generation," presented at the *Asia-Pacific Microwave Conference 1993*, Hsinchu, Taiwan, Oct. 18-21, 1993.
- (5) X-H. Qin, T. Liu, L.B. Sjogren, F. Wang, H. Shi, W-M. Zhang, C.W. Domier and N.C. Luhmann, Jr., "Advanced Technology Development for Reflectometry, Interferometry and Polarimetry," presented at the *35th*

Annual Meeting of the APS Division of Plasma Physics, St. Louis, MO, Nov. 1-5, 1993.

- (6) C.W. Domier, A. Romanowsky, R. Hsia, W-M. Zhang, H. Shi and N.C. Luhmann, Jr., "Ultrashort Pulse Radar Reflectometry," presented at the *35th Annual Meeting of the APS Division of Plasma Physics, St. Louis, MO, Nov. 1-5, 1993.*

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