Centimetre resolution time domain reflectometry using ultra-short millimetre wave pulses

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Abstract

We present a technique for making time domain reflectometry (TDR) measurements of mm-wave systems using sub-nanosecond 94GHz pulses which yields distance resolutions of a few centimetres. Pulses as short as 115ps are generated using a novel switched 7.8 to 94GHz frequency multiplier chain. Applications include the characterisation of standing waves and reflections in quasi-optical systems, the evaluation of very low return loss quasi-optical loads, and high range resolution radar.

Introduction

Time domain reflectometry is an established technique in the optical domain where it is used to characterise propagation down optical fibres. Ultrashort laser pulses are injected into the system under test and any discontinuities reflect signal back to a detector. Time-of-flight measurements are made to locate the position of the discontinuity along the fibre. In essence this is entirely analogous to pulsed radar. However, the ultrashort pulses available at optical wavelengths afford much greater range resolution than is possible with microwave radar.

Recent advances in pulsed sources now enables mm-wave TDR to be performed using sub-nanosecond pulses, achieving range resolutions of the order of centimetres.

Sub-nanosecond 94GHz Pulse Generation

Sub-nanosecond 94GHz pulses are generated using a x12 multiplier chain in which the 7.8GHz input signal is switched rapidly and the diode multipliers provide a degree of pulse sharpening [1] – see Figure 1. Control voltage pulses (min. 330ps) are provided by a 2.7Gb/s data generator. The resulting 7.8GHz pulse (min. 600ps) is presented to the multiplier chain. The pulse lengthening is thought to be due to a combination of the finite response times of the switch and the coaxial detector used. The two doublers use ultra high efficiency GaAs Schottky diodes to achieve 200mW output power.

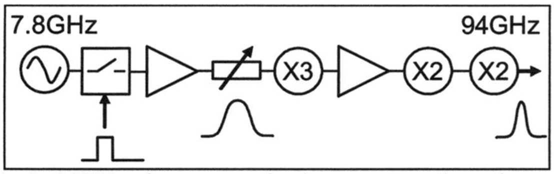

Fig. 1: 94GHz sub-nanosecond pulse generator schematic.

94GHz pulses are detected using a wide video bandwidth planar diode detector and a fast sampling scope. We use a 20GSa/s LeCroy scope with a 6GHz analogue bandwidth, but this limits our pulse measurements to about 140ps. We have been able to measure faster pulses using a demonstration model 40GSa/s 12GHz bandwidth Agilent Infiniium DSO81204A scope. This confirmed that we can generate 200ps rectangular pulses and 115ps Gaussian pulses. Note that at 94GHz, a 115ps pulse only contains about 10 cycles of carrier.

Direct Detection

The simplest reflection measurement setup uses a bistatic arrangement (separate transmit and receive ports) and direct detection using a W-band planar diode. This detector has a very fast pulse response and hence enables high range resolution measurements. However, the diode sensitivity is limited and this restricts the maximum detection range.

The maximum range resolution achievable was investigated using a bistatic pair of adjacent feedhorns and a trihedral target at 0.5m range. The target was moved in range on a translation stage and the received pulse traces recorded on the scope. Figure 2 shows that 140ps pulses detected from the target at three ranges each separated by 10mm are distinguishable. The theoretical range resolution for a pulsed radar is $\delta R = ct/2$, where c is the speed of light and t is the pulse length. For 140ps this gives δR = 21mm. This is consistent with the pulses received from the two target positions separated by 20mm, which overlap at the half-height point. Note that the definition of resolution (i.e. the level of the crossing point) is somewhat subjective. For these 140ps pulses (which may in fact be faster but could be scope limited in our measurement), a range resolution of 10mm is achievable.

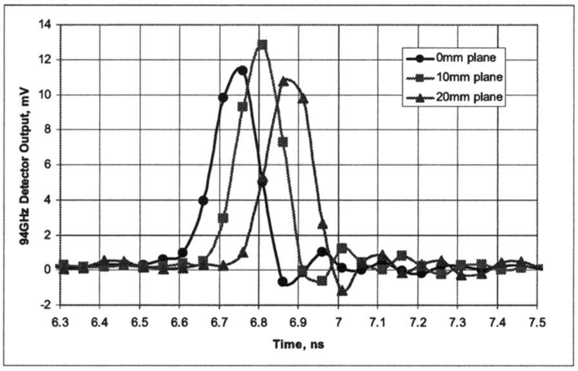

Fig. 2: 140ps 94GHz pulses detected from a target positioned at three ranges separated by 10mm increments.

Heterodyne Detection

For greater sensitivity and hence greater maximum range, heterodyne techniques can be employed in which the return signal is downconverted, amplified, filtered and detected.

A non-coherent heterodyne detection scheme was set up using an 89GHz Gunn oscillator as the LO, giving a 5GHz IF, followed by a low-noise 30dB gain amplifier and a coaxial detector. This arrangement was much more sensitive than the direct detection but the IF pulse width was broadened to 700ps. This is believed to be caused by a combination of the mixer, IF amplifier and coaxial detector response times. Note also that 140ps is actually less than one cycle of 5GHz and so the IF components may simply have been ringing in response to an impulse. Ideally a higher IF would be used but suitable

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amplifiers were not available. The range resolution of this scheme was measured in the same way described above. The 700ps pulses reflected from the target were clearly resolved at ranges separated by 50mm – see Figure 3.

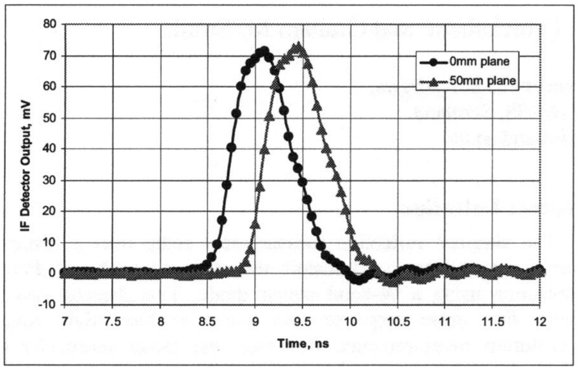

Fig. 3: 700ps 5GHz IF pulses detected from a target positioned at two ranges separated by 50mm.

Monostatic Operation

Ideally, a monostatic configuration would be used in which the transmit and receive signals share a common port, with the diplexing performed by a circulator. However, the principal difficulty with any monostatic arrangement is that of transmit-receive leakage across the circulator. During the transmit pulse, a significant level of power can leak directly to the receiver causing saturation or even damage. To mitigate this, receiver protection circuits are used, usually in the form of fast switches which blank off the receiver during the transmit pulse.

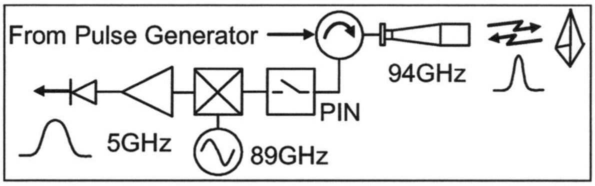

Fig. 4: Monostatic, non-coherent heterodyne detection.

Figure 4 shows a monostatic, non-coherent heterodyne receiver configured using a waveguide junction circulator and a very fast, high isolation PIN switch in front of the mixer. The PIN switch has a rise/fall time of <1ns and an on-off ratio of 60dB but an insertion loss of 2-3dB. Unfortunately, full synchronisation of the transmit pulse and PIN blanking pulse was not achieved for sub-ns pulse widths. Indeed, propagation delays in the cables carrying the timing signals become significant at these timescales. Nonetheless, it was possible to test operation in this mode using 4ns pulses, albeit with restricted output power to protect the mixer. This proved that monostatic operation is feasible but work is needed to optimise the timing synchronisation. Once complete, this system should have sufficient sensitivity to measure reflections in waveguide and quasi-optical systems.

Fully coherent operation is also possible and would permit the measurement of Doppler shifts from moving targets. We aim to implement this soon using a second multiplier chain, driven from the same 7.8GHz source, as the LO.

Transmission Measurements

One can also use the pulse generator and W-band diode detector to investigate the transmission propagation behaviour of waveguide and quasi-optical circuits.

Pulse propagation along different lengths of waveguide was characterised using 140ps pulses to measure the group velocity. At 94GHz, one would expect a propagation rate in air of 3.34ps/mm whilst the corresponding figure in WR-10 is 4.29ps/mm, calculated from the guide wavelength. The experimental value determined using various lengths of waveguide between 21 and 104mm in length was 4.2ps/mm. This is in broad agreement with the theoretical value but accuracy is limited by the time resolution of the scope (5ps).

A quasi-optical transmission set up was used to measure the added propagation delay due to slabs of dielectric being inserted in the beam. The refractive index can be calculated from the delay and the slab thickness. Good agreement was found with published values for samples of Rexolite (n = 1.59, 1.59 actual) and Fluorosint FS500 (n = 1.86, 1.88 actual).

Discussion

The generation of sub-nanosecond mm-wave pulses opens up new possibilities in the characterisation of waveguide and quasi-optical systems. We have demonstrated centimetre range resolution reflectometry at 94GHz in a bistatic configuration. Once the difficulties of using a monostatic scheme have been overcome, we aim to use this technique to characterise various quasi-optical components and systems.

The pulse generator can also be used as a radar transmitter. Pulsed mm-wave radars typically use pulse lengths of tens to hundreds of nanoseconds [2], usually limited by the modulator circuit driving the transmitter (often an IMPATT diode or a vacuum tube such as a magnetron). W-band pulsed radars with pulse lengths as short as 1-10ns have been reported [3,4,5] but the authors are unaware of any sub-nanosecond mm-wave pulsed radar being reported previously.

Conclusions

The use of a fast switch at 7.8GHz and a diode multiplier chain has enabled the generation of sub-nanosecond 94GHz pulses with output powers of 200mW. These can be used for high range resolution studies of mm-wave systems using time domain reflectometry and transmission measurements. Very high resolution radar can also be implemented, with range resolutions of the order of 10mm achievable with pulse widths down to 115ps.

Acknowledgements

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