# Manuscript for Review

## Terahertz Radar Cross Section Characterization using Laser Feedback Interferometry with a Quantum Cascade Laser

<table>
<thead>
<tr>
<th>Journal:</th>
<th><em>Electronics Letters</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID:</td>
<td>ELL-2015-2878.R1</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Letter</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>14-Aug-2015</td>
</tr>
</tbody>
</table>
| Complete List of Authors: | Lui, Hoi Shun; The University of Queensland, School of Information Technology and Electrical Engineering; Chalmers University of Technology, Department of Signals and Systems
Taimre, Thomas; The University of Queensland, School of Mathematics and Physics
Bertling, Karl; The University of Queensland, School of Information Technology and Electrical Engineering
Lim, Yah Leng; The University of Queensland, School of Information Technology and Electrical Engineering
Dean, Paul; School of Electronic and Electrical Engineering
Khanna, S; University of Leeds, School of Electronic and Electrical Engineering
Lachab, M; University of Leeds, School of Electronic and Electrical Engineering
Valavanis, Alexander; School of Electronic & Electrical Engineering
Indjin, Dragan; University of Leeds, School of Electronic and Electrical Engineering
Linfield, Edmund; School of Electronic & Electrical Engineering
Davies, Giles; University of Leeds, School of Electronic and Electrical Engineering
Rakic, Aleksandar; The University of Queensland, School of Information Technology and Electrical Engineering; |
| Keywords: | Terahertz sensing, Laser Feedback Interferometry, RADAR CROSS-SECTIONS |
Radar cross section (RCS) measurements of complex, large objects are usually performed on scale models so that the measurement is carried out in a well-controlled environment. This letter explores the feasibility of RCS measurement using a terahertz quantum cascade laser via laser feedback interferometry. Numerical simulations show that the RCS information embedded in the non-linear interferometric signals obtained from simple targets can be retrieved through numerical fitting of the well-known excess phase equation. The method is validated experimentally using a terahertz quantum cascade laser and the results are well matched with those obtained from numerical simulations.

Introduction: Radar Cross Section (RCS) characterization of a target is an angle- and frequency-dependent measure of its electromagnetic scattering behavior. Such characterization at microwave frequencies is important for military and defense-related purposes, including detection and identification of aircraft and ships, as well as countermeasures such as RCS reduction and stealth [1]. At microwave frequencies, RCS characterization requires that the measurement operates on very large objects (in terms of wavelength), such as full-scale aircrafts and ships, which is difficult to reproduce practically. The measurement process can also be time consuming and expensive. At the same time, the physical size of the aforementioned full-scale targets makes it impractical to iterate the design and testing phase in stealth and defense applications [2]. For instance, the scattered response of a target with a physical dimension of 5m at 2.6GHz can be obtained from its scaled version with the dimension of 5mm at 2.6THz. With the recent development of terahertz (THz) time domain spectrometry, attempts have been made to perform RCS characterization at THz frequencies [2]-[4]. Interest has also focused on detection and imaging of concealed weapons such as hand guns and knives at a standoff distance using THz radiation [5]-[6]. RCS characterization of these targets at THz frequencies will also be of interest in security applications. In this letter, we propose the use of a THz-frequency Quantum Cascade Laser (QCL) (a suitable high power source of THz radiation [7]) in conjunction with laser feedback interferometry (LFI) for RCS characterization. The feasibility of this approach is exemplified using square metallic plate and cube targets through simulations and experiments.

Laser Feedback Interferometry: LFI has been demonstrated in numerous sensing and imaging applications [8]-[11]. When LFI is adopted for sensing, the laser serves as a transceiver that emits a laser beam and receives the reflected beam so that no external detector is needed. The radiation emitted from the laser interacts with the external target, is reflected and partially re-injected to the laser cavity, resulting in interference between the intracavity field and re-injected signal [11]-[12]. The effect of feedback from the target can be monitored via the laser terminal voltage, which makes it ideal for work with THz QCLs [12]-[15]. Here, the laser is slowly frequency modulated such that the non-linear LFI signal is observed as a set of periodic perturbations embedded in the modulated voltage signal. The temporal separation between the peaks of the LFI signal waveform, as well as its shape and phase, depend on the length of the external cavity and the reflectivity of the external target [15]. The RCS information is thus embedded in the non-linear LFI signal.

The amount of laser feedback due to an external target can be modelled using the feedback parameter [11]

\[ C = \frac{\tau_{\text{int}}}{\tau_{L}} \kappa_{\text{s}} \sqrt{1 + \alpha^2}, \]

where \( \tau_{L} \) is the round trip time for light in the laser cavity, \( \tau_{\text{int}} \) is the round trip time for light in the external cavity and \( \alpha \) is the linewidth enhancement factor. The term \( \kappa_{\text{s}} \) is the coupling coefficient that depends on the reflectivity of the exit laser facet \( R \) and the reflectivity of the target \( R_{\text{ext}} \):

\[ \kappa_{\text{s}} = \epsilon \frac{R_{\text{ext}}}{R} (1 - R), \]

where \( \epsilon \) is the fraction of the reflected light coupled back coherently into the lasing mode.

RCS Characterization using LFI: The RCS of the target-of-interest can be given by [3]

\[ \sigma = \lim_{\kappa \to \infty} 4\pi R^2 \frac{\left| E_{\text{sc}} \right|^2}{\left| E_{\text{i}} \right|^2}. \]

where \( E_{\text{sc}} \) and \( E_{\text{i}} \) stand for the scattered and incident electric field respectively. In practice, the requirement that the distance of the scatterer from the receiver \( R \) approaches infinity can never be fully accomplished. For practical purposes, the distance \( R \) can easily be measured and the equation is reduced to

\[ \sigma = 4\pi R^2 \frac{\left| E_{\text{sc}} \right|^2}{\left| E_{\text{i}} \right|^2}. \]

In Figure 1 we explore a simple case where analytical solution for RCS is available to compare the results with RCS extracted from simulated LFI signals. Target was a 3 mm side square metallic plate with RCS computed at a series of angles (zero being normal incidence) first using the Physical Optics (PO) approximation at 2.6THz under plane wave illumination [16] and compared against the RCS values extracted from the LFI simulations under the same conditions. We now describe the process used to simulate swept-frequency LFI signal waveforms and subsequently extract the RCS from them. To simulate the RCS signals obtained using LFI with frequency modulation [15], the monostatic scattered electric field is computed using PO at 1001 equally spaced frequencies between 2.64THz and 2.601THz. The corresponding reflectance at each frequency, i.e. \( R_{\text{ext}} = \left| E_{\text{sc}} \right| / \left| E_{\text{i}} \right| \), is then used to calculate the feedback parameter via Eq. (1) and (2), which in turn is
used in the excess phase equation [11] to compute the corresponding LFI signal in the time domain. Here, the length of the external cavity was set to be 0.337 m. The entire process is repeated at each measurement aspect angle. Spatially, the aspect angles of was set to be 0.337 m. The entire process is repeated at each LFI signal in the time domain. Here, the length of the external cavity used in the excess phase equation [11] to compute the corresponding frequency sweep of 600 MHz. The emitted radiation was collimated (peak amplitude) was superimposed on the dc current leading to a linear = 0.43A and a modulating saw-tooth current signal (50 mA peak-to-

In order to test the validity of the numerical modeling a simple experiment was performed by measuring the RCS of a 3 mm metallic cube using a THz-QCL. A 2.59 THz bound-to-continent THz was operated in CW mode at a heat sink temperature of 15 K, in a continuous flow cryostat. The laser was operated at a driving current $I_{dc} = 0.43A$ and a modulation voltage $V_{mod} = 50$ mV peak-to-peak amplitude) was superimposed on the dc current leading to a linear frequency sweep of 600 MHz. The emitted radiation was collimated using a 2-inch diameter, 4-inch focal length (f/2) off-axis parabolic reflector. The target was placed on a motorized rotary stage in the collimated beam path at an external cavity distance of 0.373 m. The target therefore was fully illuminated in what was essentially a 2-inch diameter beam. The laser, electrical operating conditions, and signal recovery electronics are identical to those found in [12] and [15].

Figure 2 shows the RMS values of the LFI signals measured via the laser terminal voltage. The results are matched with those simulated using the PO approximation with diffraction corrections from the wedges using FEKO [17]. While the measured values do show some noise artifacts the major features of both the simulated and measured RMS LFI signals are in good agreement.

**Fig. 2** Monostatic Radar Cross Section of a 3mm square metallic plate. Comparison of the RMS values of the LFI signals obtained from simulation and measurement

**Conclusion:** The feasibility of RCS characterisation of some simple radar targets using laser feedback interferometry has been demonstrated through simulations and measurements. The RCS information embedded in the non-linear LFI signals can be extracted accurately by numerical fitting to the excess phase equation model. The results are well matched with the theoretical RCS values. An experiment has also been performed to obtain the RCS of a cube target. The results show that the experimentally measured LFI signals are well matched with the simulated signals. This work opens the way for RCS measurements at THz frequencies using laser feedback interferometry.

**Acknowledgments:** This research was supported under Australian Research Council’s Discovery Projects funding scheme (DP 120 103703). We also acknowledge support of the ERC “TOSCA” program, the Royal Society, the Wolfson Foundation, and the European Cooperation in Science and Technology (COST) Action BM1205. H. S. Lui acknowledges support under the UQ Postdoctoral Research Fellowship Scheme and the UQ Early Career Researcher Grant Scheme. P. Dean acknowledges support from EPSRC (UK).

H. S. Lui, K. Bertling, Y. L. Lim and A. D. Rakic (School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, QLD 4072, Australia)

E-mail: rakic@itee.uq.edu.au

T. Taimre (School of Mathematics and Physics, The University of Queensland, Brisbane, QLD 4072, Australia)


**References**


