Terahertz radar cross-section characterisation using laser feedback interferometry with quantum cascade laser

H.S. Lui, T. Taimre, K. Bertling, Y.L. Lim, P. Dean, S.P. Khanna, M. Lachab, A. Valavanis, D. Indjin, E.H. Linfield, A.G. Davies and A.D. Rakić[✉]

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. The feasibility of RCS measurement using a terahertz (THz) quantum cascade laser (QCL) via laser feedback interferometry is explored. Numerical simulations show that the RCS information embedded in the nonlinear 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 THz QCL and the results are well matched with those obtained from numerical simulations.

Introduction: Radar cross-section (RCS) characterisation of a target is an angle- and frequency-dependent measure of its electromagnetic scattering behaviour. Such characterisation at microwave frequencies is important for military and defence-related purposes, including the detection and identification of aircraft and ships, as well as countermeasures such as RCS reduction and stealth [1]. At microwave frequencies, RCS characterisation requires that the measurement operates on very large objects (in terms of wavelength), such as full-scale aircraft 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 defence applications [2]. For instance, the scattered response of a target with a physical dimension of 5 m at 2.6 GHz can be obtained from its scaled version with the dimension of 5 mm at 2.6 THz. With the recent development of terahertz (THz) time-domain spectrometry, attempts have been made to perform RCS characterisation at THz frequencies [2–4]. Interest has also focused on the detection and imaging of concealed weapons such as hand guns and knives at a standoff distance using THz radiation [5, 6]. RCS characterisation 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 characterisation. 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 intra-cavity 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 nonlinear 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 nonlinear LFI signal.

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

$$C = \frac{\tau_{ext}}{\tau_L} \kappa_{ext} \sqrt{1+\alpha^2} \tag{1}$$

where τ_L is the round trip time for light in the laser cavity, τ_{ext} is the round trip time for light in the external cavity, and α is the linewidth enhancement factor. The term κ_{ext} is the coupling coefficient that depends on the reflectivity of the exit laser facet R_s and the reflectivity of the target R_{ext}

$$\kappa_{ext} = \varepsilon \sqrt{\frac{R_{ext}}{R_s}}(1-R_s) \tag{2}$$

where ε is the fraction of the reflected light coupled back coherently into the lasing mode.

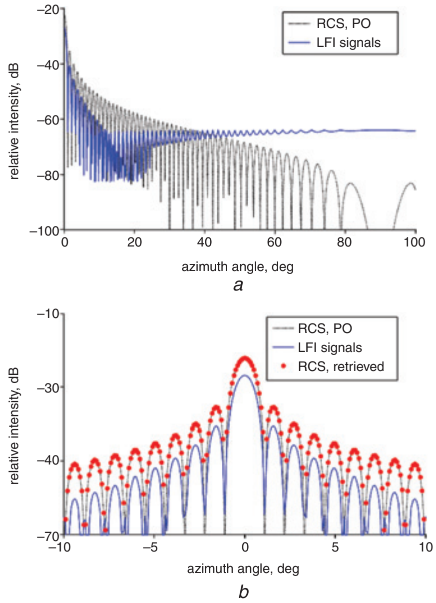

Fig. 1 *Monostatic RCS of 3 mm square metallic plate*

a Comparison of (i) theoretical RCS using PO and (ii) theoretical RMS values of LFI signals
b Comparison of (i) theoretical RCS using PO, (ii) theoretical RMS values of LFI signals, and (iii) retrieved RCS from LFI signals

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

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{|E^s|^2}{|E^i|^2} \tag{3}$$

where E^s and E^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

$$\sigma = 4\pi R^2 \frac{|E^s|^2}{|E^i|^2} \tag{4}$$

In Fig. 1, we explore a simple case where an analytical solution for the RCS is available to compare the results with the RCS extracted from simulated LFI signals. The target was a 3 mm side square metallic plate with the RCS computed at a series of angles (zero being normal incidence) first using the physical optics (PO) approximation at 2.6 THz 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 2.6 and 2.601 THz. The corresponding reflectance at each frequency, i.e. $R_{ext} = |E^s|^2/|E^i|^2$, is then used to calculate the feedback parameter via (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 ±100° with a resolution of 0.1° are considered, resulting in 2001 sampling points. The time-domain LFI signal at each of the 2001 sampling points was thus obtained, allowing the corresponding root mean square (RMS) value [12] to be computed for each aspect angle, as plotted in Fig. 1. Owing to the nonlinear nature of the LFI, the changes of the RMS value do not appear to be proportional to the RCS of the target. The corresponding target reflectivity was extracted from each LFI signal using the algorithm described in [12] which enabled us to subsequently calculate the RCS at each angle. The retrieved RCS as a function of angle is shown in Fig. 1*b* and it matches the theoretical RCS values well.

To test the validity of the numerical modelling 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-continuum QCL was operated in continuous-wave mode at a heat sink temperature of 15 K, in a continuous flow cryostat. The laser was operated at a driving current I_{dc} = 0.43 A and a modulating saw-tooth current signal (50 mA 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 motorised rotary stage in the collimated beam path at an external cavity distance of 0.337 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, 15].

Fig. 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]. Although the measured values do show some noise artefacts, the major features of both the simulated and measure RMS LFI signals are in good agreement.

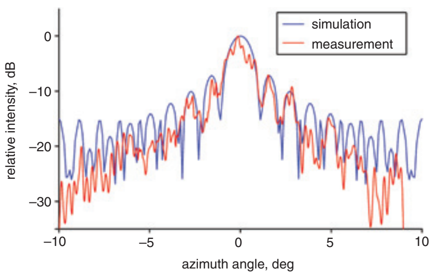

Fig. 2 *Monostatic RCS of 3 mm square metallic plate*

Comparison of RMS values of LFI signals obtained from simulation and measurement

Conclusion: The feasibility of RCS characterisation of some simple radar targets using LFI has been demonstrated through simulations and measurements. The RCS information embedded in the nonlinear 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 LFI.

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One or more of the Figures in this Letter are available in colour online.

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

✉ E-mail: rakic@itee.uq.edu.au

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

P. Dean, S.P. Khanna, M. Lachab, A. Valavanis, D. Indjin, E.H. Linfield and A.G. Davies (*School of Electronic and Electrical Engineering, University of Leeds, Leeds, LS2 9JT, United Kingdom*)

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