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Comparison of photodiode frequency response measurements to 40GHz between NPL and NIST

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Indexing terms: Photodiodes, Frequency response

The authors report the first comparison, at the national standards level, of photodiode frequency response measurements at wavelengths of 1.285, 1.319 and 1.531μm. A photodiode was measured up to 40GHz and the results were normalised to 1.319 μm using a model of the device. The average scatter in the results was ±0.12dB (2σ) below 20GHz and ±0.21dB from 20 to 33GHz.

Introduction: In a recent international intercomparison of photodiode [1] measurements, involving NPL and nine instrument manufacturers and telecommunications research laboratories, the measured electrical 3dB points of one circulated device varied from 15.1 to 19.8GHz at 1.3μm and from 9.8 to 19.9GHz at 1.5μm. These results showed that accurate RF power measurement is critical for photodiode frequency response measurements. To follow on from this work a new comparison was arranged between NPL and NIST. This would determine the achievable accuracy of our measurement systems and assess the stability of a transfer standard photodiode. In the present comparison a photodiode was measured on four systems, two at NIST (both at 1.319 μm) and two at NPL (at 1.285μm and 1.531μm).

Experiment: An InGaAs *pin* photodiode, with a nominal optical bandwidth of 20GHz, fitted with a 3.5mm RF connector, was used for this comparison. The photodiode output was DC-coupled so the device was fitted with a 3dB attenuator to provide a DC return path to ground. The attenuator also improved the electrical impedance match between the photodiode package and the measurement systems.

Measurement systems 1 and 2: Both systems at NIST used two single-mode monolithic-ring Nd:YAG lasers operating at 1.319μm [2]. System 1 measured up to 40GHz and used a calibrated RF power sensor with a 2.4mm connector and a 2.92mm adapter. System 2 measured up to 33GHz and used a calibrated RF power sensor with a 3.5mm connector.

Measurement system 3: The NPL heterodyne system [3] consisted of a distributed-feedback laser and an external-cavity distributed-feedback laser at 1.531μm. System 3 measured up to 40GHz and used a broadband RF detector with a 2.92mm connector.

Measurement system 4: The NPL modulator-based system [4] uses an 8GHz Mach-Zehnder integrated-optical modulator biased at extinction to give a levelled modulated-optical signal of approximately 30μW up to 22GHz at 1.285μm with unlevelled operation up to 25GHz. The RF power from the photodiode was measured using an RF power sensor with a 3.5mm connector.

RF power measurements are directly traceable to UK national standards in systems 3 and 4 and to NIST national standards in systems 1 and 2.

Measurement uncertainties: Below 15GHz the uncertainty in the RF power sensor calibration is the dominant factor in all four measurement systems [5]. Above 15GHz the impedance mismatch between the photodiode and the measurement system becomes the dominant source of uncertainty. The effects of the impedance mismatch can be removed using a calculated correction factor based on vector network-analyser measurements on the photodiode and the measurement system [3]. After correction for impedance mismatch, the dominant source of uncertainty above 15 GHz in systems 1, 2 and 4 is the RF sensor calibration uncertainty. Above 30 GHz, noise is the dominant source of uncertainty in system 3. System 4 requires additional corrections for laser relative intensity noise (RIN) and weak harmonically generated signals from the modulator. The uncertainty in these corrections increases with frequency and accounts for around 50% of the total uncertainty budget for system 4.

Wavelength correction: The absorption coefficient of InGaAs is a function of wavelength and so the frequency response of the photodiode will have a degree of wavelength dependence. The photodiode was modelled in an attempt to cancel this [6] effect. Parameters used in this modelling were: intrinsic-layer thickness (1.9μm) [7], diode bias voltage (+5V), absorption coefficient at 1.285, 1.319 and 1.531μm (1.2, 1.08 and 0.71 × $10^6 m^{-1}$) [8], saturated electron and hole velocities (8.6 × 10^4m/s [9] and 4.9 × 10^4m/s [10]). The ratios of the responses at 1.531 and 1.285μm to the response at 1.319μm are shown in Fig. 1. The uncertainties in these ratios were determined from uncertainties in the modelling parameters.

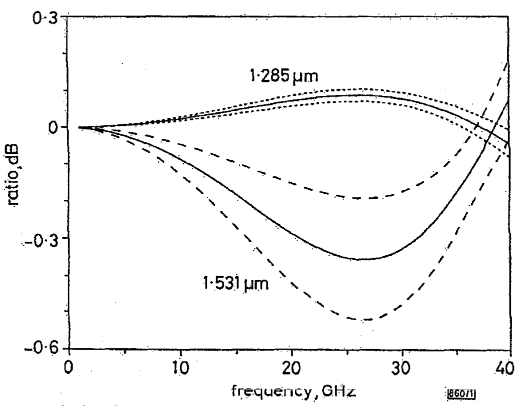

Fig. 1 *Calculated response ratio with estimated 2σ uncertainties*

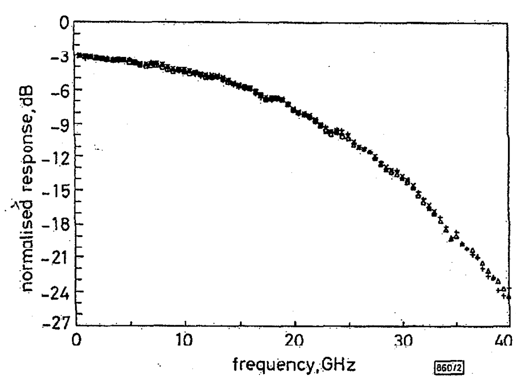

Fig. 2 *Normalised frequency response of all four measurement systems, wavelength corrected to 1319nm*

Offset from 0dB is due to a 3dB attenuator
△ NIST Nd:YAG heterodyne system –2.92mm
× NIST Nd:YAG heterodyne system –3.5mm
+ NPL heterodyne system
□ NPL IOM system

Results: The measured frequency responses of all four systems are shown in Fig. 2. All the systems measure the internal quantum efficiency of the photodiode except system 4, which measures the external quantum efficiency. The results from system 4 were normalised over the range 0.5 to 4.5GHz to the results from system 1.

Table 1: Scatter in wavelength corrected results

Frequency range, GHz	Average scatter, dB (2σ)
0.5–20	0.12
20–33	0.21
33–40	0.45

The electrical 3dB point is 16.15 ± 0.12GHz (2σ). The optical 3dB point (6dB electrical) is 22.41 ± 0.13GHz (2σ). The average scatter in the results is shown in Table 1. The divergence in the results above 33GHz is thought to be due to differences in the calibration of the RF power sensors. The source of this discrepancy is being investigated. The uncertainties (2σ, 95% confidence) of each measurement system are shown in Fig. 3.

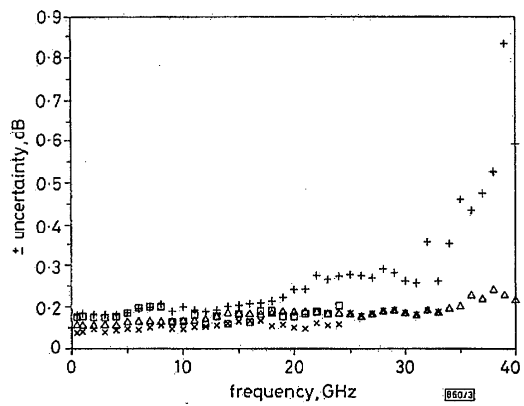

Fig. 3 *Expanded uncertainties for all four measurement systems*

+ NPL DBF heterodyne system
Δ NIST Nd:YAG heterodyne system –2.92mm
× NIST Nd:YAG heterodyne system –3.5mm
□ NPL IOM system

Conclusions: The first comparison of photodiode frequency response measurements at national standards level shows good agreement and is an important step in establishing the international standardisation of frequency response measurements, traceable to international microwave power and DC current standards. The scatter in the data is well represented by the combined uncertainties of the measurement systems up to 33GHz, but a systematic uncertainty in the RF power calibration may exist above 33 GHz. The scatter in the frequency response data near 16GHz is about three times smaller, and scatter in the 3dB point is 20 times smaller, than was reported in the previous intercomparison.

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Gated photodetector based on GaN/AlGaN heterostructure field effect transistor

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Indexing terms: Field effect transistors, Photodetectors

The authors report a 0.2μm gate GaN/AlGaN heterostructure field effect transistor which operates as a visible blind photodetector with responsivities as high as 3000A/W for wavelengths from 200 to 365nm. The responsivity falls by three orders of magnitude for wavelengths greater than 365nm. Using a CW He-Cd laser (wavelength 325nm), we measured a response time of order 0.2ms. A model explaining the detector operation is in good agreement with the experimental data.

The demonstration of GaN based blue light emitting diodes [1] and visible blind photoconductive and photovoltaic sensors [2, 3] confirms a great potential of this material system for optoelectronic applications. In a recent publication [4], we reported 0.2μm gate AlGaN/GaN heterostructure field effect transistors (HFETs) which operated as microwave amplifiers to temperatures as high as 300°C with maximum oscillation frequency f_{max} and cutoff frequency f_T of ~70GHz and ~22GHz, respectively, at room temperature [5, 6]. We now report the operation of these HFETs as gated visible blind photodetectors.

The epilayer structure and processing details for the gated photodetectors are identical to those for the short gate HFETs [4] (see inset in Fig. 1). In Fig. 1, we plot the HFET drain current (at V_{ds} = 10V) as a function of the gate bias with and without illumination from a 2mW He-Cd laser from the sapphire substrate side. Using the photocurrent and dark current values from Fig. 1 and the device illumination geometry, we estimated the responsivity values plotted in Fig. 2 (solid line).

Using a mechanical chopper and the synchronous detection of the photocurrent, we measured the response time of the HFET photodetector. These transient waveforms indicated an approximate response time of 2×10^{-4}s.

In Fig. 3, we plot the spectral dependence of the responsivity in relative units. As seen, the responsivity falls sharply by several orders of magnitude for wavelengths larger than 365nm (which corresponds to the *i*-GaN bandgap). This clearly demonstrates the visible blind operation of our gated photodetector.