Application of Metal-Semiconductor (MSM) Photodetectors for Transverse and Longitudinal Intra-Bunch Beam Diagnostics

Ralph J. Steinhagen (CERN), Toshiyuki Mitsuhashi (KEK), Mark J. Boland (Australian Synchrotron)
Thomas G. Lucas, Roger P. Rassool (The University of Melbourne, Australia)

The performance reach of modern accelerators is often governed by the ability to reliably measure and control the beam stability. In high-brightness lepton and high-energy hadron accelerators, the use of optical diagnostic techniques is becoming more widespread as the required bandwidth, resolution and high RF beam power level involved limit the use of traditional electro-magnetic RF pick-up based methods. This contribution discusses the use of fibre-coupled ultra-fast Metal-Semiconductor-Metal Photodetectors (MSM-PD) as an alternative, dependable means to measure signals derived from electro-optical and synchrotron-light based diagnostics systems. It describes the beam studies performed at CERN’s CLIC Test Facility (CTF3) and the Australian Synchrotron to assess the feasibility of this technology as a robust, wide-band and sensitive technique for measuring transverse intra-bunch and bunch-by-bunch beam oscillations, longitudinal beam profiles, un-bunched beam population and beam-halo profiles.

1. MSM – Photodetector

In order to preserve benefits of working in the optical domain the optical receiver must match the performances of the optical front-end and fibre transmission. Same MSM-PDs as for the fill-pattern-monitor at the Australian Synchrotron.

2. MSM-PD Receiver Topologies

- Studied receiver topologies:
  a) MSM-BT – classic balanced Bias-T
     • easy wide-band implementation
     • presently only option for f_s > 12 GHz
     • bandwidth limited to f_m – 3f_r
     • MSM are current-sources – charge-up of AC-decoupling capacitor for high-duty factor
     • 10-20% rolloff – 100 kHz
  b) MSM-TIA – bal. Transimpedance Amplifier
     • larger gain/lower noise-figure
     • true DC-response
     • Bandwidth given by: 1/(2π*R_C*C_P)
     • OP4847 (BW>3 GHz)
     • Linearity limited by OpAmp
  c) APD – Time-Correlated Single Photon-Counting using avalanche photodiode
     • used at LCLS, SLSA, LHC, C.A. Thomas et al., Nature 439 (2006)
     • based on integration – not applicable for fast intra-bunch motion
     • high gain/low noise (r.f. linearity, provided a well separated bunches)
     • APD: dead time
     • Max. of one photon/turn – 10-20 ns (Integration (SLS) up to ~30 minutes)

3. MSM-BT Bandwidth Tests at the CTF3 – Combiner Ring (CR)

The high-power CLIC drive-beam is produced by interleaving four 3 GHz bunch trains. The lower RF harmonics diminish in favour of (ideally) only a single line at 12 GHz, seen in the spectra for the fourth bunch, and confirms the MSM-PD bandwidth. The prevailing lower harmonics indicate an imperfect batch-by-batch interleaving.

4. Sensitivity and Linearity Tests at the Australian Synchrotron

Achieved ~10^4 vs. theoretical limit of 10^6 dynamic range, limited rather by ENOB of digital acquisition chain than amplifier/Bias-T. Linearity of MSM-BT and MSM-TIA in agreement with APD data down to the 10^-4-level. Limit for MSM-BT: compensation of the droop caused by the AC-coupling, notably cable reflections. Limiting factor is the accuracy of the point-spread-function (PSF) relating the actual charged particle distribution to the measured SL-beam distribution.

5. MSM-Beam Halo Measurements

Measured large spot size dominated by chromatic aberrations as the full visible spectrum was taken into account to maximise the incident light power. Dominating limiting factor is the accuracy of the point-spread-function (PSF) relating the actual charged particle distribution to the measured SL-beam distribution.

6. MSM Applications being studied:

- Fibre-coupled MSM-PDs being studied as an back-end option for:
  A) Electro-Optical-BPM (EO-BPM), &
  B) Synchrotron-Light-BPM (SL-BPM)

- Limiting factor is the accuracy of the point-spread-function (PSF) relating the actual charged particle distribution to the measured SL-beam distribution.

Advantages:
- Non-invasive, more robust w.r.t. EMC
- Handling of high beam power
- For accelerator typical distance of 100 m: OM4 (GRIN) fibre bandwidth ~ 47 GHz vs. 7/8 coaxial cable ~ 600 MHz
- Position resolution sensitivity: SL-BPM ~ 10^-3, EO-BPM ~ 10^-4 (can reduce crystal length ~400 V half-wavelength)

SL-BPM Measurement Example:

- EO-BPM Lab Prototype Tests:
  - Position accuracy: 1.5 mm
  - True 80 MHz bandwidth

EO-BPM Lab Prototype Tests:

- Studies ongoing in view of mechanical and prototype integration at the SPS...