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

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Abstract

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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. The amplification schemes, achieved sensitivities, linearity, and dynamic range of the detector setup are presented.

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APPLICATION OF METAL-SEMICONDUCTOR-METAL (MSM) PHOTODETECTORS FOR TRANSVERSE AND LONGITUDINAL INTRA-BUNCH BEAM DIAGNOSTICS

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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. The amplification schemes, achieved sensitivities, linearity, and dynamic range of the detector setup are presented.

INTRODUCTION

The most notable advantage of optical systems is the bandwidth that can be achieved over cable lengths of 100 m which are typical distances for accelerators: commonly used broad-band coaxial achieve about 600 MHz [1, 2], which is easily outperformed by standard OM4-type fibres that achieve up to 47 GHz [3]. In addition, optical systems allow some wide-band signal conditioning that are easier to perform in the optical than electrical domain, such as signal summation, signal difference, wide-band delays, wavelength multiplexing, fast switching etc. While much of the signal conditioning can be done optically, the signal needs ultimately to be converted and (at least partially) processed in the electrical domain before being sampled by a high-speed or high-resolution ADC.

MSM-PD RECEIVER

In order to preserve the benefits of working in the optical domain, the optical receiver must match the performances of the optical front-end and fibre transmission. Our studies are based on the same MSM-PDs used for the earlier developed fill-pattern-monitor operated at the Australian Synchrotron [4, 5]. These MSM-PD are SMA-connectorised, robust, very low-noise, cost-effective and with a typical rise-time of 30 ps being ideally suited for high bandwidth measurements. Their parameters are summarised in Table 1. One of the advantages of MSM-PD

Table 1: MSM Properties, given for $\lambda = 850\,\text{nm}$ [5].

Radiant sensitivity	0.3	A/W
Max. Input Power ($t < 1\,\text{ns}$)	< 50	mW
Spectral response	[450,870]	nm
Dark Current	100	pA
Current noise	1.0	$\text{fA}/\sqrt{\text{Hz}}$
Terminal Capacitance C_D	≈ 0.3	pF
10%-90% rise time t_r	≈ 30	ps

over e.g. PIN, CMOS or CCD-type photo-detectors is their negligible transit time, and that they can be biased in the (common) backward as well as forward direction. This facilitates an efficient means to produce difference or sum signals by inverting the given bias voltage U_{bias} polarity. The balanced topology also suppresses the dark current, ambient light and other common mode noise [6, 7]. The bias voltage can be used (within limits) to control the radiant sensitivity, for example, to null the signal of the combined detector. For the prototype, we evaluated the optical receiver topologies illustrated in Fig. 1.

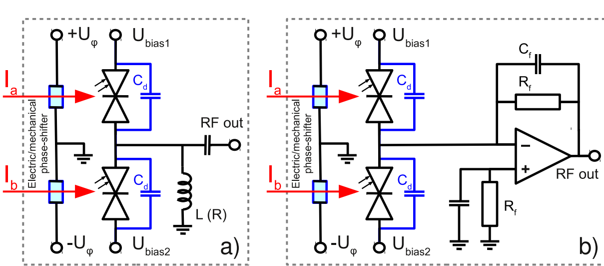

Figure 1: Receiver schematics for the MSM-PD: Balanced Bias-T (BT, left) and DC-coupled balanced transimpedance amplifier (TIA, right).

For the nominal receiver, light is coupled directly from the fibre onto the MSM-PD and their current is summed in a central node. For the classic balanced Bias-T (BT) the DC-return path is provided by an inductor L and the output AC-coupled using a capacitor, adjusted to the desired DC-cut-off frequency. The advantage of this topol-

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ogy is that it is simple, very wide-band and also used in commercial Bias-Ts and the existing fill-pattern-monitor (FPM) at the Australian Synchrotron [4]. The topology uses high-value inductors for the DC-return, which is appropriate for voltage sources, but in the scase of current sources and signals with a high pulse duty factor, this may cause the AC-coupling capacitor to charge up, reduce the effective radiant sensitivity and in turn causes important signal non-linearities of subsequent bunches. Since the MSM-PD currents are typically very small, a lower impedance resistor R replacing L can alleviate this, however with the constraint that the bandwidth and transconductance are fixed and equal to 50 Ohm. The corresponding 3 dB-bandwidth $f_{bw-BT} = 1/2\pi RC_D$ is essentially limited by the lumped terminal capacitance C_D of the MSM-PDs, other parasitic RF-PCB, or connecting cable capacitances. As this Bias-T is intrinsically AC coupled, the base-line needs to be restored if absolute peak amplitudes are needed (e.g. for beam intensity measurements), as for example described in [8]. While the Bias-T remains the preferred and only choice for very fast responses beyond the few Gigahertz range, a larger transconductance-bandwidth can be achieved with (balanced) transimpedance amplifiers (TIA), schematically shown in Fig. 1. The corresponding bandwidth relationship is given by $f_{bw-TIA} \sim \sqrt{GBP/4R_fC_D}$ which is limited rather by the available gain-bandwidth-product GBP of the used operational amplifier, than the lumped capacitance C_D at the inverting input of the MSM-PD and parasitic capacitances of the connectors, PCB traces, and operational amplifier. The transconductance is defined by the feedback resistor R_f.

If required, the TIA topology can preserve the true DC response which eliminates the need for a base-line restitution algorithm. For this application, the additional R_f connected to the non-inverting input compensates for the input bias-current imperfections of the operational amplifier, and C_p to mitigate the noise contribution of this additional resistor at the input. An additional small feedback capacitor C_f is sometimes needed to provide an additional low-pass pole to cancel the instability caused at high frequencies. This was not necessary for the operational amplifiers (OPA847 & OP657) used in the tested prototype, since the required capacitance was below 1 pF and in the order of the parasitic PCB capacitance of the pad for R_f.

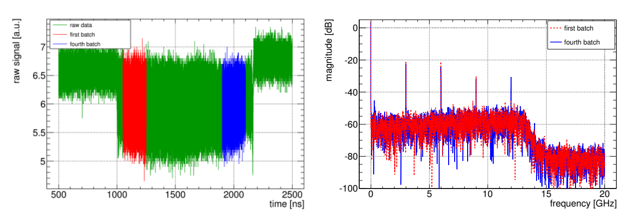
Based on the prototypes build, for the same transconductance of 513 Ohm (N.B. parasitic $C_D \approx 4\,\text{pF}$), the BT-topology option delivers a bandwidth of 77 MHz, whereas the TIA could achieve a bandwidth of about 550 MHz. Thiss illustrates nicely the benefits of a TIA compared to a BT for bandwidths below or in the order of a few GHz. Higher TIA gains are limited by the maximum available GBP and/or parasitic input capacitance and imperfections of the op-amps' SOT23-6 chip package. Even higher gains may require an all-on-chip design, with a tight MSM-PD and amplifier integration using chip bonding technology. For the test with beam, the constructed TIA prototype has been limited in bandwidth to about 80 MHz in favour of a higher transconductance of 25 kOhm. The achieved combined noise figure for the TIA of $5.2\,\text{pA/sqrtHz}$ (without MSM-PD attached) matched the theoretic expectations from a design $4.8\,\text{pA/sqrtHz}$ point of view.

EXPERIMENTAL RESULTS WITH BEAM

A series of tests have been performed in order to demonstrate the various application possibilities and MSM-PD receiver performances in a real accelerator environment. The experiments related to the assessment of the bandwidth were carried out at the CERN CLIC Test Facility (CTF3), and the experiments related to assessing the dynamic range, linearity and resolution at the Australian Synchrotron.

Bandwidth Tests

The CTF3 at CERN is used to develop the technology and assess the feasibility of the next generation linear lepton collider, aimed at providing centre-of-mass energies at the TeV scale [9]. The MSM-PD experiments were conducted at one of the view-ports of the CTF3 combiner ring (CR) nominally used by the streak-camera [10]. The CR is part of the chain that produces the 12 GHz high-power CLIC drive-beam, by accumulating and interleaving four batches of electron trains, each having a 3 GHz bunch structure. During the process, the lower RF harmonics diminish in favour of (ideally) only a single 12 GHz spectral line. Figure 2 shows a typically high-bandwidth time- and corresponding frequency-domain signal of the first and last batch. The AC-coupling and base-line recovery of the



(a) time-domain (b) frequency-domain

Figure 2: High-Bandwidth MSM-BT time- and corresponding frequency-domain signal taken at the CTF3 combiner ring. Fourier spectrum of the first and fourth injected batch. The 12 GHz RF bunch component and about 13 GHz roll-off due to the limited digitizer bandwidth are visible.

MSM-BT after the four batches have been extracted is visible. An enhanced 12 GHz spectral line is visible for the fourth batch, confirming predicted MSM-PD bandwidth. The prevailing of the other lower RF harmonics indicate an imperfect batch-by-batch interleaving for this specific measurement. This information could be used to tune the recombination process of the CTF3-CR.

Dynamic Range and Linearity Tests

The Australian Synchrotron storage ring is a 3.0 GeV electron ring with a circumference of 216 m, situated in Melbourne, Australia [11]. Most of the MSM-PD receiver tests use the synchrotron light emitted by the electron passing through one of the main bending magnets, separated

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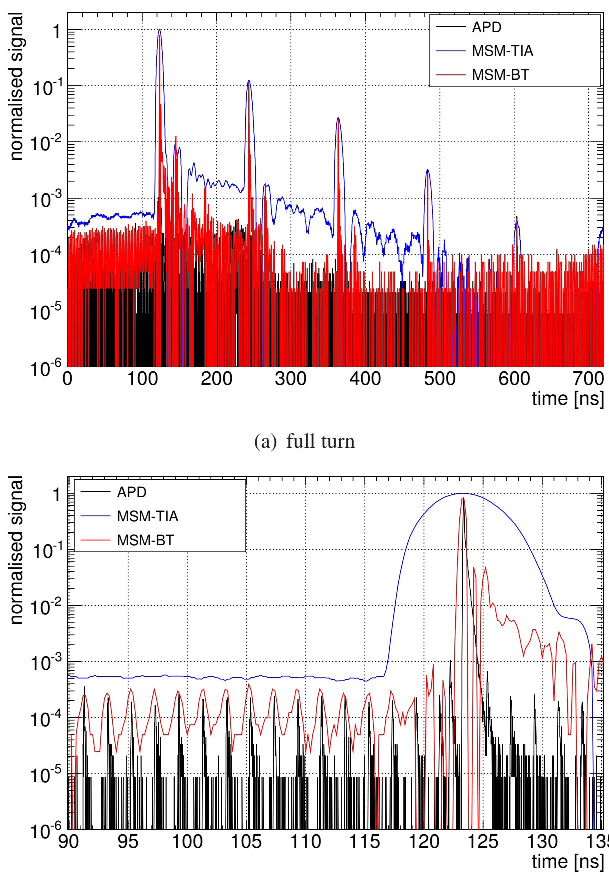
from the X-rays using a vertical mirror above the beam axis, focused through a lens, and then guided into an optical diagnostic beam line (ODB [12]).

The dynamic range, linearity and resolution of the system were assessed using a avalanche photo-diode (APD) in a time-correlated single photon-counting mode of operation [13]. This method implies important integration times, particularly for large accelerators such as the LHC. Nevertheless, it provides a de-facto 'golden standard' in terms of linearity: for bunch signals that are separated by more than the APD dead-time, the vertical resolution is basically only affected by statistic and the (very low) probability of two photons arriving within the same APD dead-time interval.

The MSM-BT and MSM-TIA were acquired similar to, and MSM-BT base-line droop compensated as outlined in [8]. The comparative measurement is shown in Fig. 3.



(a) full turn

(b) zoomed on first bunch

Figure 3: Comparison of APD, MSM-BT and MSM-TIA signals. The accelerator has been filled with single separated bunches corresponding to beam currents of 10, 1.0, 0.1, 0.01 and 0.001 mA. Particle spill into neighbouring buckets, in particular for the larger bunch intensities, and bandwidth differences between APD and MSM-BT (600 MHz) and MSM-TIA (80 MHz) are visible.

Each system achieved an approximate dynamic range of about 10^5, with the APD being limited by the maximum bin count of the TDC, and the MSM-BT and MSM-TIA being limited by the direct time-domain digitisation of the used oscilloscope (100k turn average). In terms of linearity, the MSM-BT and MSM-TIA measurements correlate with the APD data down to the 10^{-4} level. The limit for the MSM-BT is given by the compensation of the droop caused by the AC-coupling, notably the compensation for cable reflections. For the MSM-TIA the linearity is determined and compatible with the spurious-free-dynamic-range (SFDR) of the used operational amplifier (OPA847). Higher SFDRs are possible with a different choice of operational amplifiers, but in trade-off with a reduced system bandwidth. While the MSM-PD have a theoretic instantaneous dynamic range of about 10^8, for practical purposes the available range is limited by the digital acquisition, with the about constant product of effective-number-of-bits (ENOB) and achievable bandwidth approaching fundamental limitations indicated in [14].

FUTURE MSM-PD APPLICATIONS

The application of fibre-coupled MSM-PD are being studied for the following specific cases: electro-optical- (EO-BPM) and synchrotron-light-based Beam Position Monitors (SL-BPM) [15], schematically illustrated in Fig. 4. Both system share the same light-to-fibre cou-

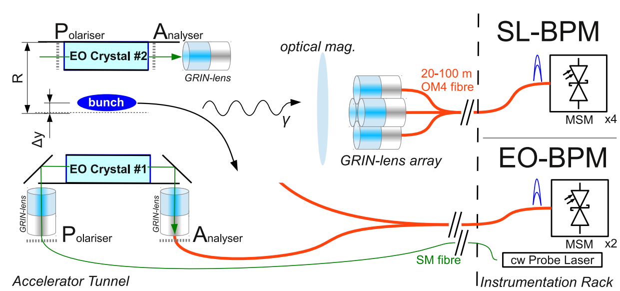


Figure 4: EO- and SL-BPM Schematic.

pling, transmission, and fibre-coupled, high-speed MSM-PD in a custom-made balanced RF biasing circuit, kept along the other sensitive processing electronics in a low-EMI and radiation environment.

Electro-Optic BPM

The EO-BPM under development exploits the Pockels effect of a set of two EO-active crystals located at opposite sides of the beam vacuum chamber [16, 17]. Similar to classic BPMs, the ratio of the difference over the sum of both crystal's birefringence is a measure of the beam position in relation to the half-aperture R. Initial laboratory tests indicated that the interferometric approach is rather susceptible to thermal drifts and mechanical stability across the two crystals, and thus a polarization-based intensity modulation approach was chosen. Arranging the (in-fibre polarisation) controller-crystal-analyser locally simplifies and eliminates the need for polarisation-maintaining fibres to and from the tunnel. Initial prototype tests were performed in the lab, guiding a planned initial deployment at the SPS

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Synchrotron-Light BPM

The SL-BPM, similar to laser stabilisation in DVD or Blue-Ray players, measures the beam centroid position by focusing the synchrotron-light cone emitted by the particle beam onto a 2x2 diamond formation of GRIN-lenses/fibres located and that is connected to a set of MSM-PDs on the far end [15]. The advantage of this scheme is that the relative position change scales with the relative SL-beam spot size σ_z on the focal plane, rather than the vacuum-pipe aperture R. This gives a substantial amplification factor, at the cost of a reduced operational range. Still, in cases where only small, relative or high-frequency oscillations need to be resolved (i.e. for Q/Q' or instability diagnostics), this is an acceptable compromise.

Beam-Halo Monitoring

Similar to the SL-BPM, the same receiver topology could be further extended to a wider (line-)array of GRIN-lenses and MSM-PD that cover and monitor the SL-beam spot distribution as a whole. Compared to other PDs, MSM-PDs provide higher-bandwidths and larger instantaneous dynamic range which could be exploited to measure beam sizes down to a bunch-by-bunch basis. An exemplary distribution measured with the MSM-PD at the Australian Synchrotron is shown in Fig. 5. The measurement has

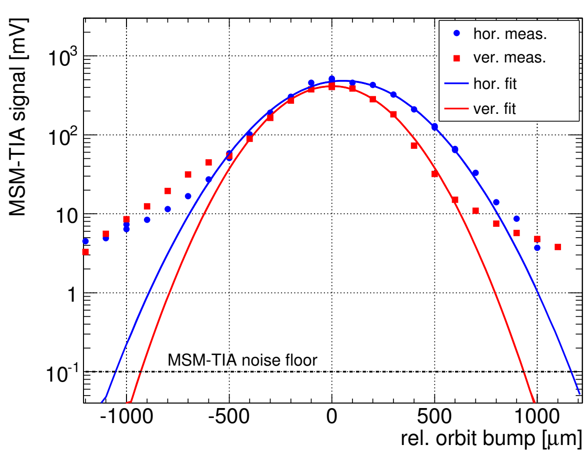

Figure 5: Measurement and gaussian-fit of the SL beam spot size ($\sigma_x = 269.28 \pm 0.03\,\mu$m,$\sigma_y = 228.41 \pm 0.04\,\mu$m).

been obtained by moving the orbit and thus the SL beam spot across the MSM-PD while recording the corresponding signal levels. The overall large spot size is dominated by chromatic aberrations and other lens effects as the full visible SL-spectrum was taken into account to maximise the incident light power. However, similar to the measurements shown in Fig. 3, it demonstrates the ability of the MSM-PD to resolve bunch shape variations down to the 10^5 level. Still, the dominating limiting factor of this measurement, besides the afore-mentioned ADC bandwidth-ENOB limit, is the accuracy of the point-spread-function of the optical transport system that relates the actual charged particle distribution creating the synchrotron light with the measured beam spot distribution in the focal plain.

CONCLUSION

MSM-PD provide an alternative, dependable means to convert signals deriving from electro-optical and synchrotron-light based diagnostics systems. The optical receiver must match the performances of the optical front-end and fibre transmission, in order to preserve the benefits of working in the optical domain. Beam measurements performed at CTF3 and the Australian Synchrotron confirm bandwidth, dynamic range and linearity for the tested receiver topologies.

In combination with the tested fibre-coupling, this opens the possibility to further exploit the MSM-PD 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.

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