APPLICABILITY OF THE AM-PM CONVERSION METHOD TO BEAM POSITION MONITORING OF ELECTRON BEAMS ACCELERATED IN S-BAND FREQUENCY RANGE*

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Abstract

In this paper the applicability of the amplitude-to-phase-conversion (AM-PM) method to beam position monitoring (BPM) purposes in the S-Band frequency range is investigated. The proof-of-principle experiment is done by AM-PM-processing of capacitive pickup signals induced by a 6 MeV electron beam generated by an S-Band accelerator. It is demonstrated that the amplitude of the AM-PM's DC output is proportional to transverse beam offsets. The development and validation of a varactor-based 3 GHz phase shifter as well as a planarized AM-PM receiver module are presented. Experimental data show that AM-PM conversion is also feasible in the microwave range if suitable devices and appropriate fabrication technologies are used.

INTRODUCTION

AM-PM conversion is well-known as a BPM signal processing technique with several benefits as well as drawbacks compared to log-ratio or difference-over-sum. The summary of BPM signal processing methods given in [1] points out that AM-PM is the most expensive of the three aforementioned methods. However, in [2], its large dynamic range and the superior performance over Δ/Σ for small beam displacements are stated as major advantages.
When it comes to read-out electronics, the work presented in [2], [3] and [4] relies on hybrid junctions with a delay-line extension on one port to generate phase modulation from amplitude modulation. Amplitude independent beam position information is finally obtained by using zero-crossing detectors and XOR logic devices.
This paper presents the adaptation of AM-PM-functionality into the microwave frequency range where analogue comparators or logic devices are not available any more. Instead, diode mixers can be used as phase discriminating devices. The applicability of AM-PM conversion in the S-Band is proved by a prototype receiver which successfully processed pickup signals generated by an S-Band 6 MeV electron beam. Moreover, a planarized AM-PM-receiver is presented employing a branchline coupler hybrid, an SMD mixer as phase discriminator and RF limiters to avoid amplitude dependence. The realization of an electronically tuneable phase shifter needed for phase matching of the input signals is also described. Advantages and disadvantages of the proposed receiver are finally compared.

* Work supported by Bayerische Forschungsstiftung in the project "MEDieMAS - Effiziente Bestrahlungsgeräte für Krebstherapie (Efficient radiation systems for cancer therapy)", file number AZ-735-07

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MICROWAVE THEORY OF OPERATION

Figure 1 depicts a schematic overview of the most important devices required by the AM-PM conversion method, with a and b representing opposing pickup signals.

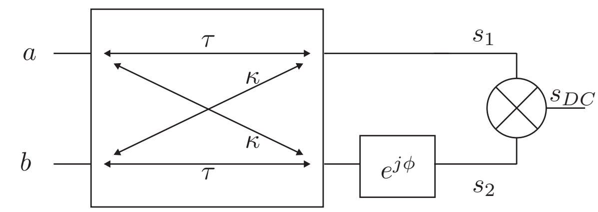

Figure 1: Sketch of an AM-PM frontend comprising one hybrid, delay line and mixer per measurement plane.

The hybrid is a 3 dB-π/2-coupler of the branchline type and the delay line is dimensioned for a phase shift of $\phi = 90$ degrees. With $\tau = 1/\sqrt{2}$ and $\kappa = j/\sqrt{2}$, it follows from elementary RF theory that the two signals

$$s_1 = \tau a + \kappa b = 1/\sqrt{2} \cdot (a + jb) \quad (1)$$

$$s_2 = j(\kappa a + \tau b) = 1/\sqrt{2} \cdot (-a + jb) \quad (2)$$

have equal amplitude but opposite phase:

$$\hat{s}_1 = \hat{s}_2 = 1/\sqrt{2} \cdot \sqrt{a^2 + b^2} \quad (3)$$

$$\varphi_{s_1} = -\varphi_{s_2} = \arctan(b/a) \quad (4)$$

Thus, the amplitude ratio is converted into phase difference: $\Delta\varphi = \varphi_{s_1} - \varphi_{s_2} = 2\arctan(b/a)$.
The diode mixer's I-V-curve is a nonlinear function of the applied voltage $v_d(t)$. In the case depicted in Fig. 1, $v_d(t)$ is a superposition of the two signals $s_1(t)$ and $s_2(t)$ with frequencies $\omega_1 = \omega_2$ and phase angles $\varphi_{s_1} = -\varphi_{s_2}$. Thus, the DC-part of the diode current can be calculated by evaluating the quadratic term of the current's Taylor expansion:

$$\begin{aligned} i_d(t) &= ...v_d^2(t)... = & (5)\\ &= ...2\hat{s}_1\hat{s}_2\cos(\omega_1 t + \varphi_{s_1})\cos(\omega_1 t + \varphi_{s_2}).. & (6)\\ &= ...\hat{s}_1\hat{s}_2\cos(\omega_1 t - \omega_1 t - \varphi_{s_1} + \varphi_{s_2})... & (7)\\ &= ...\hat{s}_1\hat{s}_2\cos(-\Delta\varphi)... = & (8)\\ &= ...\hat{s}_1\hat{s}_2\cos[2\arctan(b/a)]... & (9) \end{aligned}$$

It follows from (9) that the mixer's DC output is a direct representation of the amplitude ratio induced by beam displacements, showing a nearly ideal linear slope around center position (as experimentally demonstrated, compare Fig. 7). However, it heavily depends on the amplitude of the individual pickup signals if no limiting devices are used.

PROOF OF PRINCIPLE

To investigate the basic functionality of the AM-PM-method for electron beams inside an S-Band accelerator, a two-channel prototype was built employing off-the-shelf connectorized components and a branchline coupler fabricated in-house.

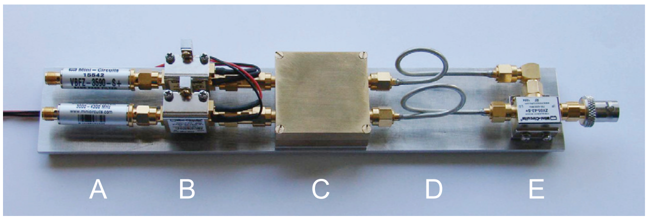

Figure 2: Discrete implementation of AM-PM prototype.

Figure 2 depicts the prototype module. Two RF signals are fed to 3 GHz-bandpasses (A) and amplified by commercially available RF amplifiers with 17 dB gain at 3 GHz (B). The gain is necessary to drive the mixer into the region of nonlinearity as required for the multiplication process. The hybrid inside the cover (C) (manufactured on CLTE-AT 254 µm substrate) shows input matching values < -25 dB, isolation > 25 dB and phase imbalance ± 2 degrees which indicates excellent RF behavior. The connection to the RF mixer was achieved by bent semi-rigid lines (D) with one loop being slightly larger in diameter to account for the additional 90 degrees phase shift (see Fig. 1). Finally, the downconversion module (E) is a MiniCircuits double balanced mixer which provides IF accessibility down to DC and good channel isolation due to the symmetric RF and LO feeds. Phase matching was done by a mechanical tuner in front of the prototype's upper input in these experiments. In this first prototype setup no limiters have been used in order to keep the circuitry as simple as possible. Thus, the output signal shows strong amplitude dependence: Lab measurements at 3 GHz center frequency resulted in an on-center sensitivity of 35 mV/dB for +7 dBm RF input power which dropped over 20 mV/dB at 0 dBm to 15 mV/dB for -7 dBm, respectively.

After the successful lab demonstration of feasibility, the prototype module was hooked on a test stand employing a 6 MeV, 25 mA, 3 GHz electron beam and capacitive pickups of the button type which can be manually displaced with regards to the beam [5]. Figure 3 depicts the measurement results.

As predicted by theory, the output signal generated by the AM-PM conversion method depends on electron beam offsets, demonstrating AM-PM-applicability to the S-Band frequency range. The non-zero error voltage for 0 mm pickup displacement indicates slightly off-centered beam, which also causes an overall deviation from a linear slope. The bench measurements show a different DC offset at equal RF power levels which is due to the bent semi-rigid lines causing phase variations even at the slightest touch.

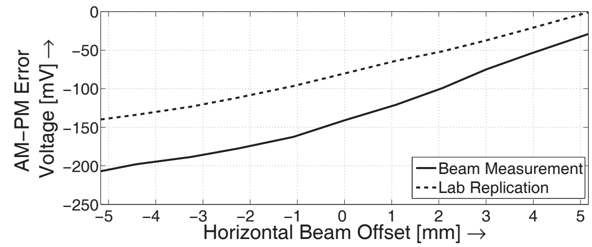

Figure 3: Solid: DC error voltage generated by AM-PM-processing of an S-Band beam moved horizontally between capacitive pickups. Dashed: Lab measurements using the same receiver but RF generators emulating the test stand's beam signals (RF power is -7 dBm at the mixer input).

PLANARIZED AM-PM RF CIRCUITS

The measurements conducted with the prototype successfully demonstrated the basic applicability of the AM-PM method to S-Band if microwave multipliers are used instead of logic devices. However, the results also revealed the drawbacks of the discrete setup, especially the touch-sensitive bent transmission lines at a location in the circuit where phase stability is crucial. For these reasons, two planar devices have been built from scratch to overcome the problems stated above: A planar 3 GHz phase shifter for RF input phase matching and a fully-planarized two-channel AM-PM receiver module.

Electronically Tuneable Phase Shifter

A microwave phase shifter to be used for the AM-PM-method should be capable of shifting the phase of a 3 GHz RF wave continuously over a range of 180 degrees. Therefore, commercially available shifters based on switched delay lines are of only limited use. It was decided to fabricate a phase shifter from scratch using varactor diodes as tuneable elements. These devices offer a DC-voltage dependent capacitance which, in reflection configuration, can be used as electronically adjustable reactive load. The phase shifter employing four varactors as well as RF chokes and capacitors for RF-DC-separation is depicted in Fig. 4.

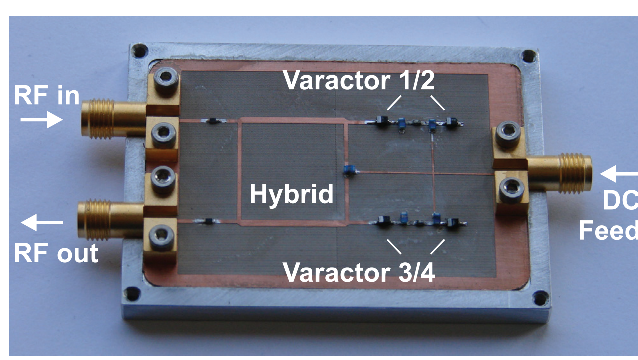

Figure 4: Planar phase shifter employing four varactor diodes Infineon BB 837 (0,55...6,6 pF over 0...25 V).

Figure 5 depicts the phase shifter's performance showing a phase range of 220 degrees at 0...15 V DC, insertion losses below 2.5 dB (imbalance over DC bias can be considered during receiver calibration) and good agreement between Harmonic Balance simulation and measurement.

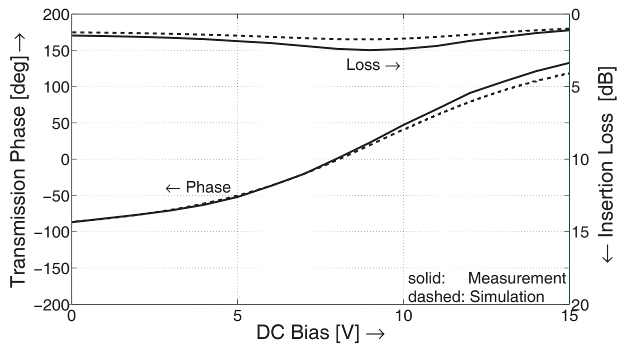

Figure 5: Adjustable phase range and insertion loss of planar varactor-based phase shifter.

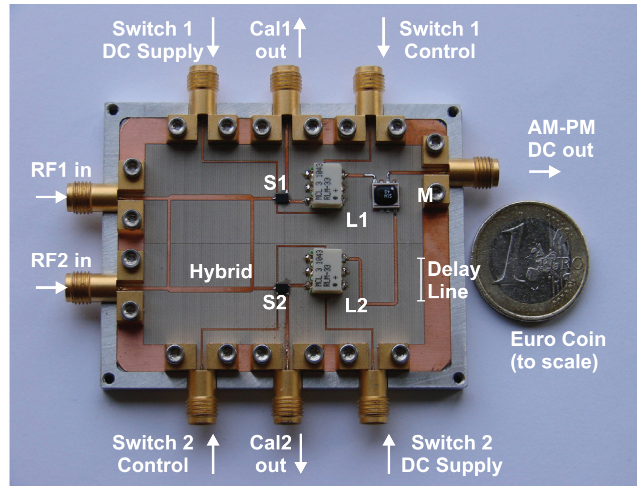

Figure 6: Planarized AM-PM receiver module fabricated on Arlon CLTE-AT substrate (S1/S2: Switches, L1/L2: Limiters, M: Mixer).

Planarized AM-PM Receiver Module

The planar version of the AM-PM receiver comprises the 3 GHz, 3 dB-hybrid already used in the prototype as well as an SMD version of MiniCircuits' mixer ZX05-43. Moreover, RF switches (Infineon BGS12AL7-4) are used for the calibration procedure which requires direct access to the individual hybrid outputs. RF limiters (MiniCircuits RLM-33) are used to suppress amplitude dependence. Figure 6 depicts the module whereas Fig. 7 shows measurement results for varying RF input power levels.

Figure 7 reveals that the obtained on-center sensitivity of the AM-PM receiver is 45 mV/dB. This nearly doubles the value achievable by commercially available log-ratio amplifiers like AD8317 (Analog Devices) or hmc611 (Hittite), typically showing RF-DC-conversion sensitivities around 25 mV/dB (dotted line in Fig. 7). Consequently, the position noise induced by the mixer diodes' Schottky voltage noise would be lower by a factor of two using AM-PM. However, due to the non-ideal behavior of the RF limiters, amplitude dependence is not fully suppressed. As depicted in Fig. 7, varying RF input power levels between +7 and +10 dBm do not affect the DC output at all. At +18 dBm, however, the on-center deviation of 70 mV indicates that a calibration is needed when the beam current is changed.

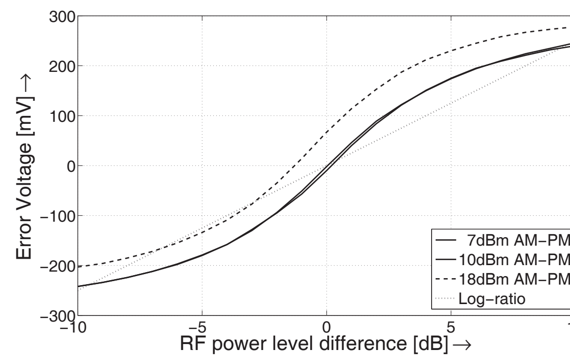

Figure 7: Measurement results of AM-PM-generated error signal for different power levels compared to a exemplary $V_{DC} - P_{RF}$-curve generated by log-ratio processing.

CONCLUSION

The AM-PM conversion method has been investigated for electron beams accelerated in S-Band. Basic functionality was demonstrated by a prototype setup. An improved planarized two-channel receiver module was manufactured and successfully tested for AM-PM operation. 45 mV/dB sensitivity (twice as high as conventional log-ratio detectors) was achieved, with the drawback of amplitude-depending DC output caused by non-ideal RF limiters.

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