DESIGN OF A FULL-CUSTOM ACCURATE I-Q MODULATOR

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Abstract

The I-Q modulator is a key component in a Low Level Radio-Frequency (LLRF) system for the amplitude and phase control of the electromagnetic wave inside the accelerating cavities. Its amplitude and phase unbalance have a strong impact on the dynamic and accuracy of the feedback loops. For some frequencies, commercial I-Q modulators are available. Nevertheless, these components are usually designed for broadband communication purposes, and their unbalances may be incompatible with the amplitude and phase stability requirements for demanding accelerators. Since LLRF systems are typically narrow-banded, i.e. limited to a few Megahertz, an customised I-Q modulator could be designed by optimising each subcomponent at the desired frequency in term of coupling, matching or harmonics. This approach that guarantees high accuracies with a full-custom design is presented in this paper.

INTRODUCTION

An I-Q modulator is a 4 ports device with 3 inputs (RF, I and Q) and one RF output. The RF input feeds a 90°, 3dB hybrid whose outputs are modulated by the 'I' and 'Q' inputs independently with 2 passive or active mixers. The signal paths are finally recombined in phase to provide the RF output. Typical commercial linear I-Q modulators present an amplitude and phase unbalance of respectively about 1 dB and ±5°.

The custom design will apply to the LLRF system for the SPIRAL2 accelerator dedicated to radioactive beams production [1], with a centre frequency at 88 MHz, a maximum bandwidth of ±1 MHz, a 0.3 dB amplitude balance and less than 1° phase balance. Simulations and optimisations are carried out with Ansoft Designer™ [2]. This EDA software supports the non-linear harmonic balance analysis required by the mixer design. As an additional benefit, the custom design also provides a comprehensive model for the LLRF system simulation, which is necessary to assess the final performances. Naturally, the approach presented herein is easily extended to other frequencies with a minimum adaptation.

LUMPED ELEMENTS HYBRIDS

The 90° hybrid is a critical part in the design of the I-Q modulator since it directly impact on the unbalances. At 88 MHz, lumped elements hybrids should be considered advantageously, while branch-line or rat-race hybrids are left for higher centre frequencies. Two topologies have been considered.

First order filters based hybrid

Since a first order lowpass filter (CR cell) gives a 45° phase delay at the cutoff frequency and its highpass (LR cell) counterpart a 45° phase advance, a simple hybrid

could be built with 2 filters in parallel. However, the input and the 'I' output would not be in phase. An additional 5-order highpass filter is used in that purpose (Figure 1).
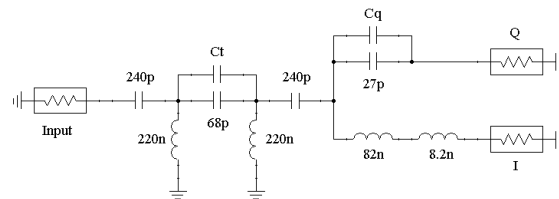

Figure 1 : Parallel lowpass-highpass filters 90° hybrid, all ports are 50 Ω referenced

Filters are synthesised with the dedicated tool in Ansoft Designer™. Capacitances and inductances are taken from vendor libraries, respectively AVX and COILCRAFT, accounting for parasitic elements. Trimmers 'Cq' and 'Ct', with Q = 300, adjust respectively the phase difference between 'I' and 'Q' outputs, and the input and the 'I' output. There optimal values given by Optimetrics™ [2] are 5.76 pF and 20.9 pF. The phase balance in the bandwidth 87-89 MHz is better than 0.005° while the amplitude unbalance does not exceed 0.11 dB and the maximum input VSWR 1.12 (Figure 2).
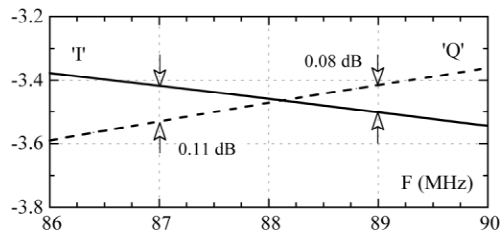

Figure 2 : Filters based 90° hybrid transmittances in dB

Custom octave-band hybrid

The topology presented above provides excellent wide-band quadrature accuracy. But the amplitude unbalance increases monotonically while moving away from the centre frequency. If wider bandwidth is desired, an alternate topology [3] offers a better trade-off between phase and amplitude balance (Figure 3).
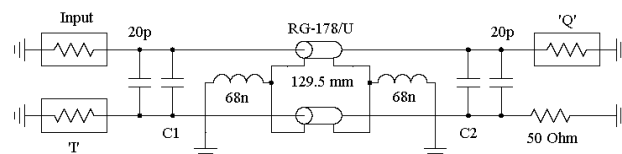

Figure 3 : Wider bandwidth 90° hybrid

Optimum values for trimmers 'C1' and 'C2' are found to be 5.27 pF and 3.56 pF. Transmittances are shown in Figure 4 with an excellent input VSWR of 1.07. The only drawback comes from the need of 2 coaxial lines, which at 88 MHz turns out a little cumbersome for a printed board implementation, with a length of 129.5 mm. This makes the first topology preferable for the present design.
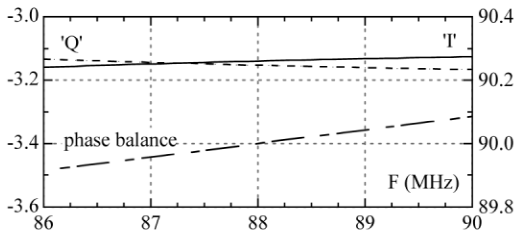
Figure 4 : Custom octave-band 90° hybrid (transmittance in dB : left scale, phase balance in degree : right scale)

MIXERS

For an I-Q modulator, either active FET transistor mixers or passive diode mixers can be used. The former provide higher RF output power and lower harmonics, usually available in integrated circuits. In contrast, the latter are better suited for LLRF applications owing to their robustness, ease for the design and full simulation with generic EDA tools. Double balanced star mixers [4] (Figure 5) will be considered for their DC 'IF' modulation capability. The 'IF' input will be driven by 'I' or 'Q'.
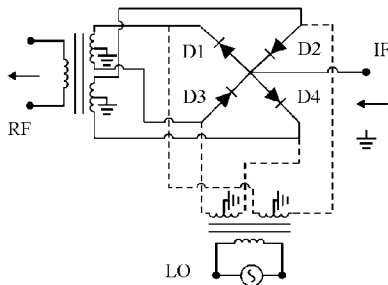

Figure 5 : Double balanced star diode mixer (unmatched)

RF transformers

Each transformer at the LO or RF side could be manufactured with 5 coils on single toroidal ferrite core. However, in order to minimise the parasitic capacitances and couplings between coils and to increase the design robustness, a combination of 3 SMD MINI-CIRCUITS transformers (ADTT4-1, impedance ratio 4) has been preferred in a configuration where one transformer, used as a balun, drives the 2 others. The high impedance coils are connected to each other. The high frequency behaviour of the transformers conditions the distribution of the harmonics at the 'RF' output. A wideband transformer model [5] (Figure 6) is needed for a reliable harmonics analysis.
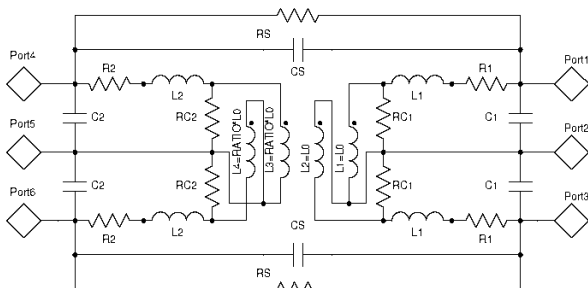

Figure 6 : RF transformer wideband model

Table 1 : Transformer model parameters

Transformer	ADTT4-1
L0	18.523uH
K coupling	0.999851
CS	0.353 pF
R1	2.387 mΩ , R2 = 2 R1
C1	1.310 pF, C2 = 2 C1
L1	4.054 nH, L2 = 2 L1
RC1	956 Ω, RC2 = 4 RC1

Model parameters (Table 1) estimated from the transformer characteristics in the nominal bandwidth (120 MHz) provide an extension of the characteristics at higher frequencies. Physical and symmetrical reasons lead to relations between parameters at the secondary and the primary through the impedance ratio.

Ports driving and matching

The maximum available power and the harmonics reduction at the 'RF' output, the dynamic and linearity to the 'IF' input decided the choice of Schottky barrier diodes, which depend on the maximum current capability, parasitic capacitances, and saturation characteristics. After investigation, diode BAT54W (PHILIPS) has been considered. The 'IF' port in Figure 5 is driven with a maximum current of 10 mA through a 2 serial resistances of 250 Ω tee network with a parallel capacitance of 2 pF, from a voltage source. Further matching is not needed for this low frequency (1 MHz max.) port. On the contrary, a very good matching of the 'LO' port is essential to preserve the amplitude and especially the phase balance of the 90° hybrid. A 13 dBm pump power represents an optimal choice regarding to 'LO' third harmonic and sideband spurious. This non-linear matching is realised at 88 MHz with the harmonic balance analysis. A VSWR of 1.04 was obtained with a LC network (parallel capacitor at the transformer side). The matching of the 'RF' output is obtained similarly. Normalised values of lumped elements and capacitor trimmers are given in Table 2. A serial low value (0.5 to 2 Ω) resistor could also be added to improve the matching.

Table 2 : Mixer ports matching elements

Mixer port	'LO'	'RF'
Inductance (nH)	220+56	330+33
Capacitance (pF)	75+9.8	75+6.7

Sign '+' means in serial for inductors and parallel for capacitors

Linearity, harmonics and spurious response

At the maximum 'IF' modulation frequency of 1 MHz, the linearity of the 'RF' voltage versus the 'IF' voltage up to 5 V, where the mixing product power reaches the value of -14.5 dBm, is excellent. It is characterised by a R-squared value of 0.99986. The power spectrum including 'LO' harmonics and sideband spurious at the 'RF' output in the worst case, i.e. for a 5 V 'IF' voltage modulation, is shown in Figure 7. The sideband spurious rejection adjacent to 88 MHz is better than 40 dB.
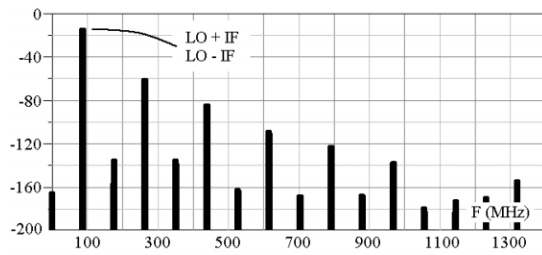
Figure 7 : Power spectrum of the 'RF' output

Figure 8 : Phase to amplitude modulation cross-talk, relative modulation in percentage

I-Q MODULATOR

A commercial MINI-CIRCUITS power combiner (ADP-2-1) is used at the I-Q modulator output. It gives a perfect amplitude balance and 0.07° phase balance in the design bandwidth, with an insertion loss of 3.21 dB, arm isolation of 29.5 dB, and VSWR of 1.01. For the simulation, it is modelled with an ideal directional coupler cascaded to an ideal 2-ways combiner.

Dynamic amplitude and phase unbalance

The matching of the mixer 'LO' port was optimised for an 'IF' voltage of 2.5 V. A modulation at 'IF' port results in a small mismatch at the 'LO' port and dynamic unbalances because of the non-linear behaviour of the diodes. Hybrids presented in Figure 1 and Figure 3, provide their excellent balances only on perfectly match loads. When the I-Q modulator operates as a single sideband modulator, where the 'I' and 'Q' are driven in quadrature, the sideband rejection relates directly to the amplitude and phase balances [6], and gives a practical way to assess the hybrid balances. The dynamic unbalances and the sideband rejection are computed (Table 3). The unbalances stay constant below 0.5 V.

Table 3 : Dynamic unbalances and sideband rejection

V(I&Q)	0.5V	1.5V	2.5V	3.5V	4.5V	5.0V
A. balance.	-0.25	-0.18	-0.06	+0.07	+0.19	+0.25
P. balance.	+0.61	+0.36	+0.01	-0.37	-0.77	-0.97
SB reject..	41.6	45.7	72.7	45.7	39.5	37.5

Amplitude balance in dB, phase balance in degree

Table 3 clearly shows a compromise between the modulation range and the I-Q modulator accuracy. A better phase balance is obtained with a matching of the mixer 'LO' input at a lower 'IF' voltage, and a reduced modulation range. For example, if the modulation were limited to 2.5 V, the amplitude and phase unbalances could be contained in respectively 0.2 dB and 0.4°.

Amplitude and phase modulation cross-talk

For the LLRF applications, it is crucial that the amplitude and phase could be modulated independently, since perturbations may involve mainly amplitude or phase modulations. For example, beam charge jitters fall in the first case and micro phonic vibrations in the second. Figure 8 shows the phase modulation in 4-quadrants to the amplitude modulation cross-talk, which does not exceed 0.5 %, equivalent to an isolation of 46 dB.
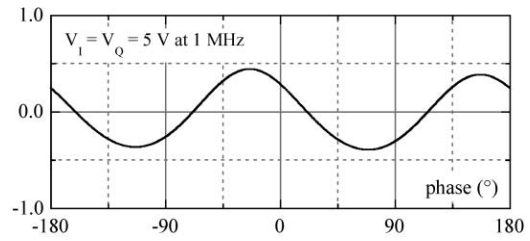
Conversely, an amplitude modulation should not induce a significant phase modulation as defined by the interception points 'i1' and 'i2' in Figure 9. Results are shown in Table 4. The phase offset mainly due to the modulator amplitude unbalance does not represent a limitation in a LLRF application. The 'I' and 'Q' data are obtained in simulation with an ideal I-Q demodulator.
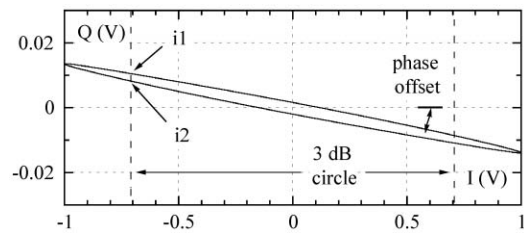

Figure 9 : Method for phase to amplitude modulation cross-talk calculation (at 0° phase shift)

Table 4 : Phase offset amplitude to phase modulation cross-talk at different phase shift (units in degree)

Phase shift	0	30	60	90
Phase offset	0.80	0.63	0.15	0.71
Phase modulation	0.18	0.22	0.82	0.83

CONCLUSION

An example for the design of a high performance full-custom I-Q modulator using a standard EDA tool (Ansoft Designer) is demonstrated. It must be emphasized that a special care should be paid to the whole design and not only to the 90° hybrid design. 'RF', 'I' and 'Q' input levels turn out to be critical for the I-Q modulator accuracy.

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