IMS 2011 Student Competition
Optical to Microwave Converter
Design Proposal

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March 1, 2011

Design in General

In this paper a design proposal for an Optical to Microwave Coverter will be made. The design is intended to meet the following criteria:

- IP3 point of 38 dBm
- Output power of 23dBm
- An operating frequency of liking, and at least a bandwidth of 10 % of the selected frequency frequency, **selected as 2Ghz and a bandwidth of 200Mhz**
- An output signal power to total power ratio of 5%

Considering the design requirements given by the host, we came into an agreement upon a topology provided as seperate design blocks:

- Optical divider
- Photodiode array
- Impedance matching circuitry
- Power combiner
- Bandpass filter

As an optional design consideration, a pre-distortion stages and an amplifier may be implemented into the design, as shown. A power supply regulator will also be implemented with proper RF routing.

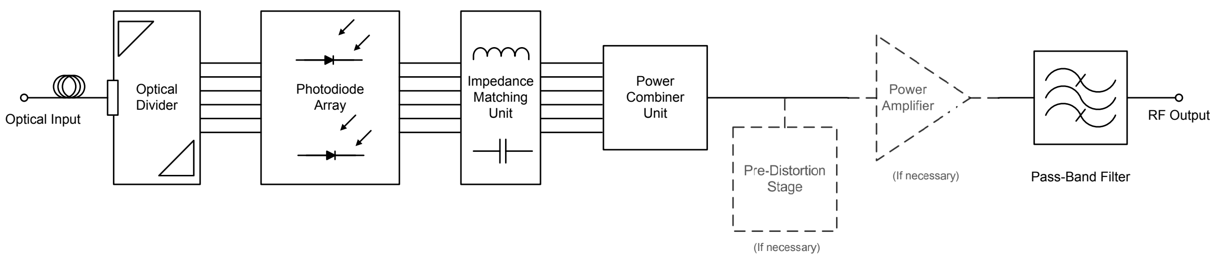

Figure 1: Diagram of the design. The stages that inclusion of are a matter of design choice are shown with dashes

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Out of the requirements that are to be met, maintaining the proposed linearity (IP3 point at 38dBm) in overall seems to be one of the most challenging tasks. For that, we focused on drawing as much power as possible from the incoming signal, since any amplification would result in a distortion that would inevitably lead to an decrease in overall distortion performance of the circuit.This design strategy is also beneficial for efficiency requirements. Another design approach we had was to minimize the effect of active components, or eliminate them altogether if possible. Considering the junction capacitance of the photodiode and that the output power requirement is not relaxed for higher the operating frequency goes, we selected our operating frequency as 2 Ghz, the possible minimum.

Optical divider

The incoming laser signal will be divided into signals of equal power, in order to acquire as much of the power that can be included into the circuitry without driving the photodiodes into saturation.[1] [2] With this topology, we can ensure that we can improve distortion performance of our circuit and maximize power that is drawn from the diodes. This arises from the fact that each photodiode can be operated within its linear regime and safety margin, without compromising from the power hat can be fed into the next stage. The division will be maintained with an planar optical splitter, which should be selected such that uniformity in power distribution is favored mostly, so that the power combiner circuitry is not loaded with a nonuniform power distribution. We plan to distribute the signal into six of the photodiodes, though this number may be subject to change. Relatively being one of the most linear component with a DSO of -65 dB when compared to amplifiers and combiners, dividing the signal gives an advantage in harvesting as much power as possible with minimal distortion.

Photodiode array

The photodiode array will include single photodiodes with their junctions reverse biased. The reverse bias voltage of each photodiode will be maintained on 12V, which may be subject to revision on the further stages of the design phase, since it presents an opportunity to fine adjust the trade-off between noise and frequency response. Since the depletion layer of the junction will narrow down when reverse biased, the junction capacitance will be lowered. This particular capacitance is related to the bias voltage with $\mathcal{O}(C^{-1/2})$, which means that it gets harder to lower it down with bias voltage. [3] This plays a crucial part on our design, since a signal with frequency of 2Ghz is grounded with a noticeably low impedance even with capacitances of few picofarads.

The topology that ensures that the diode remains in reverse bias is called as photoconductive, which is a circuit topology that favors bandwidth and response time over dark current generated by the Nyquist-Johnson noise. Practically, this noise affects the whole spectrum of the microwave region, in which the frequencies not of our interest will be filtered out with the filters and the matching circuitry.This particular noise is generated within the diode or any remaining conductive media. Thus, sources of noise in different detection stages can be modeled as uncorrelated white noise sources. Since the probability of having the noise signal $n_1(t)$ doesn't effect other noise signals $n_i(t)$, when combined in power, these noise signals will be reluctant to cancelling each other.

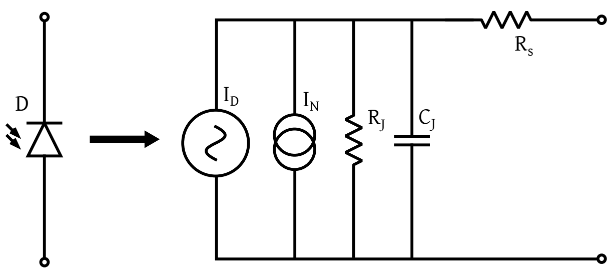

Figure 2: AC Model for the photodiode.

A photodiode can be modeled with a power (referring to the optical power) controlled current source I_D, a noise source with all types of noises of interest are incorporated in I_N, a junction capacitance C_J , a shunt resistance R_J and a series resistance R_S. (Figure) The controlled current source should be able to maintain this current for a range of impedances following the idealized current source, including the junction capacitance. Larger the impedance that is connected as load, higher the power will be extracted from the photodiode. This is ultimately limited with the aforementioned junction capacitance and will present difficulties in higher operating frequencies.

Impedance matching circuitry

In order to avoid from high insertion loss , which is a result of impedance mismatch between photodiode and power combiner , an impedance matching circuit is required. Since output impedance of photodiode will be highly capacitive at the operating frequencies, considering the maximum power transfer theorem , impedance looking from photodiode to inside the circuit should be complex conjugate of its output impedance. Another requirement about the impedance matching circuit is its bandwidth. Because our design criteria is to obtain at least 10 % relative bandwidth of center frequency , impedance matching circuit should be introduce any mismatch at this bandwidth. After photodiode modeling , this circuit will be designed , to achieve a good match between the photodiode and power combiner. Because of this bandpass requirement, this matching stage will operate also like a bandpass filter , and any noise produced by the photodiodes , in the frequencies not our interest will be filtered .

Power combiner

An RF power combiner will be employed to combine power obtained from photodiode array. It has to be able to operate at the selected center frequency and band width. Any commercially available RF power combiner with a low insertion loss, high isolation between input ports and high linearity can be used. Since, RF combiners are mostly designed in order to work with source and load impedances of 50 Ω it will not introduce any mismatch to circuit. The choice of combiner will vary according to number of used photo diodes in previous block. While two, three or four way RF power combiners are commercially available, it is hard to find a proper six way power combiner which operates at the selected frequency. However, it is possible to use two 3-way and one 2-way power combiner or three 2-way and one 3-way power combiner in order to build a 6-way power combiner. Mentioned possible usages are shown below.

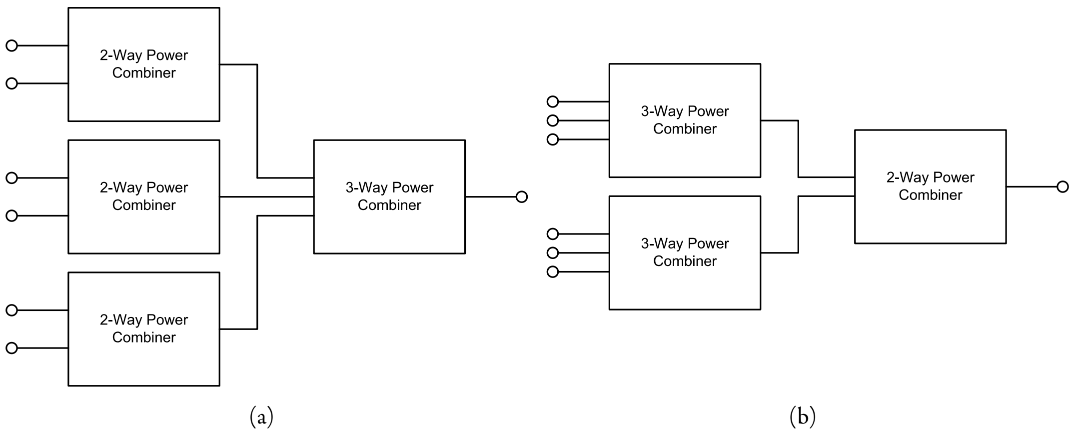

Figure 3: Two different power combiner topologies, (a) with three two-port combiners followed by a three-port combiner and (b) with two three-port combiners followed by a two-port combiner

It is important to consider the repeatability of the combiners if it is required to use more than one combiner. Although combiners can be accepted as linear, it will be important to choose the topology which introduce less distortion to the circuit. Since combiners are passive circuits elements no need to consider about power consumption. If any proper RF power combiner which has desired features does not exist commercially, an N-way RF power combiner similar to Wilkinson power combiner will be designed. Wilkinson power combiner is selected because it provides a high degree of isolation between ports. Since Wilkinson power combiner can be match to all ports it will not cause any mismatch. [4] There are two main configuration for a N-way Wilkinson power combiner which are "star" and "delta" configurations. Since delta configuration is becoming complicated and hard to manufacture for increasing N, star configuration will be preferred. However it is hard to design a N-way Wilkinson power combiner for N higher than 3 in 2D structure using microstrip lines because of crossover resistors. An alternative solution could be to use of lumped circuits elements, the lumped-element design is much easier to realize.[5]

Distortion Compensation

The nonlinearity of the power amplifier is one of the main bottlenecks of the design phase. There are a couple of methods to cope up with this effect, and how the selection is made is a determining factor for the outcome. There are three main linearization techniques for amplifiers, the following are a quick glance to properties of each:

Negative feedback

Negative feedback can be considered as one of the easiest methods that can be applied in order to improve linearity of an amplifier. The fact that applying a negative feedback leads to a trade-off from closed loop gain, and it may not be the best solution for us, since we are in need of a certain amount of gain in order to meet the output power requirements. Cartesian feedback is an example from many feedback types available for use which is also pretty common. Besides a trade off from the gain, in many feedback systems, stability becomes an issue. [6]. With varying environmental parameters such as temperature, at our frequencies, maintaining feedback comes out to be a delicate issue of engineering the phase of the signals. Considering that we'd like to favor simplicity, negative feedback looks like a candidate only if we can obtain enough gain to trade linearity with.

Feedforward

A second approach would be building a feedforward network, such that the distorted signal is fed into a second signal path, subtracted from a replica of the original signal, obtaining only the components that cause distortion on the signal. (Figure) After the signal that has only the components of the harmonic distortion is also amplified, it is coupled back to the main signal path destructively, thus eliminating the upper harmonics. T_1 and T_2 are delay elements that compensate for the delays that are generated in the amplifiers. Last two amplifiers that have gains of A_0 and $1/A_0$ respectively, should have perfectly linear characteristic. All delay elements and amplifiers' gains should be perfectly matched in order to prevent unwanted drifts in the circuit. Phase alignment is also a critical task in feedforward systems.

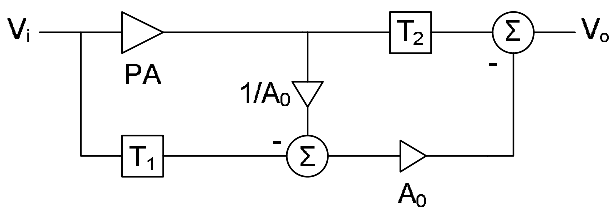

Figure 4: Schematic illustration of the feedforward linearization technique

Although feedforward method provides good intermodulation distortion suppression and does not cause any constraint for the bandwidth, it brings complexity to our design. It is not the best choice for us, since two amplifiers out of three need to have a very linear transfer characteristics. When compared to amplifiers that have the best distortion performance available on the market, the design requirement for harmonic distortion (IP3 > 38dBm) remains too high to be maintained without a price to be paid with high power cosumption regarding the stages with gain.

Predistortion

A third way to obtain a linear transfer function is implementing additional transfer functions that compansate for the distortion by completing its gain up to a constant. This method in general is called as "predistortion technique", though "postdistortion" technique is also possible but not prefered due to the high swing it must retain, since the signal is amplified beforehand. Predistortion technique is based on creating a transfer characteristic with nonlinear components which forms a complementary circuit for the next stage's distortion characteristic. In Figure , the basic operation scheme of RF predistortion technique is shown, which displays graphically that when two stages which have complementary distortion characteristics to each other are cascaded, the overall system will have a linear transfer function.

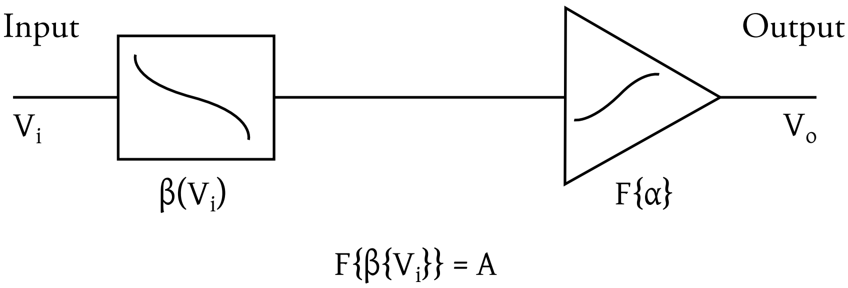

Figure 5: Predistortion stage with RF amplifier

The biggest advantage of predistortion technique is that since correction is applied before the gain stage, insertion loss is no more critical, so design criteria is just to have a predistortion stage which has desired transfer function. In Figure , a basic predistortion stage which includes an attenuator consists of resistors and anti – parallel diodes with a bridge configuration is shown [7] [8]

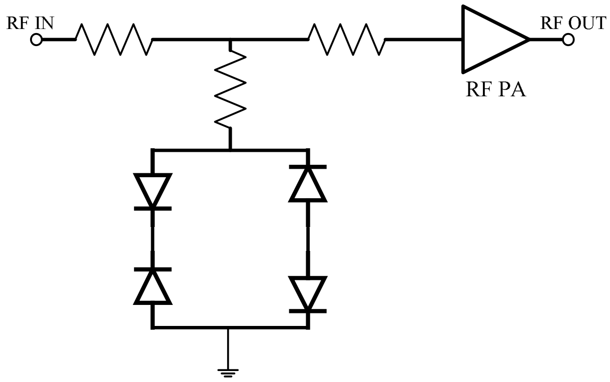

Figure 6: A simple predistortion circuit

In our design, if we need an amplification stage we will use predistortion technique to suppress harmonics which causes distortion. If in any case, power combiner also introduces notable amount distortion, an additional predistortion stage may also be included in the design. Predistortion circuits are easier to implement in our design when compared to feedforward method.

Power amplification stage

A power amplifier with low power consumption, high linearity and relatively high power gain will be selected.

Bandpass filter

A bandpass filter will be incorporated into the output stage, so that the noise outside the frequency window is filtered out, with the higher harmonics of pure sinusodial signals. The filter can be realized as a high order Chebyshev filter.

Power Supply

Though the power supply will be maintained on the field, there are some precautions that should be taken with regard to the power supply design. Besides of the active and passive circuitry that will filter power supply ripples out, the power rails will be designed meeting the needs of an RF circuit. The current sinks in the circuitry that will draw currents with high frequency, such as the photodiodes, or the amplifier, a group of capacitors should be present just next to the supplied pin, in order to compensate for the low performance in supplying current in high frequencies. When an amplifier, or a photodiode tries to draw high current in periods corrensponding to our central frequency, these capacitors will act as supplies, a buffer that compensates for the low performance of the supply nets themselves. Capacitances of those capacitors will be selected such that at least one can maintain a capacitive behaviour, is in a regime that the frequency in interest is well below its self resonant frequency (SRF). [9] These capacitances obtain an inductive characteristic beyond the its SRF, thus each of them will react as low-pass filters till that partifular frequency. A power plane will be avoided, since noise immunity of different power grids suffer from that particular approach, but a ground plane is beneficial for the relaibility of our microstrips and good control over the line impedances. Decoupling of the power lines is within our concern, since we're using multiple detectors, and a possibly an amplifier, a feedback may result in problems in stability, and coupling of noise, thus a worse noise cancellation. As a result, the power grids will be designed in a star configuration,which satisfies our concerns about decoupling, noise immunity and PSRR.

Facilities

It could be assistive to mention about the design and measurement facilities that are to be used during physical realization. The circuitry will be realized on Taconic© TSM-DS3 or TSM-30 substrate. Numerical simulations have been and will be ran in AWR Design Environment© Microwave Office ®2009. IP3 measurements will be made with the help of a vector signal generator (Rohde & Schwarz®SMBV100A) and a spectrum analyzer (Agilent ®E4402B). S parameters of the photodiode and evetually the model parameters of it will be obtained with a network analyzer (Rohde & Schwarz®FSH8).

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