Passive RF components design for an academic radar using Sonnet

Michael D. Enders

Department of Electrical Engineering and Computer Science
Syracuse University, NY 13244, USA
mdenders@syr.edu

Abstract: This paper describes the efforts in designing a few passive RF components for a basic radar system that was conceptualized, designed and implemented in a single summer semester at Syracuse University. An overview of the process is provided, including determining components requirements, selection of components structures, EM simulation/design and test results.

Keywords: Passive components, Radar, Sonnet

1. Introduction

Radars are often complex systems that can take several years to design and implement and cost up to millions of dollars. Usually graduate students interested in working with such systems take courses related to it or specific theoretical courses such as Radar Engineering. Seldom is there the opportunity for hands on experience apart from internships in industry or association with a research group in the field. The Syracuse University's 2011 summer course ELE791 – Practical Software Radio extended its usual syllabus and provided a challenge to design and implement a software defined radar system with hardware components designed by the students. No predetermined kit of components was set (unlike the kits in [4]) so the students played an important role by either designing them or selecting appropriate off-the-shelf components. The course counted with the collaboration of local industry for access to equipment / software / material.

This paper discusses most of the passive RF components designed for this radar system. First a brief overview will be provided on the required RF components for the project as well as the general specifications chosen for each one of them. The actual component design in a circuit simulator is then discussed which is where the components' structures were selected. Details of the EM simulations follow. Test boards and measurements of components performance are then presented and finally a conclusion is given.

2. Components requirements

The components requirements were meant to be relatively loose to allow for flexibility in both the design of the particular component as well as in its use in the radar system as a whole. To visualize the types and purpose of passive components needed it is helpful to view a simplified schematic of the radar system in which the RF part is shown in a little more detail (Fig. 1). The passive components required are outlined with dashed boxes in red. They are: a band pass filter, a coupler and a low pass filter.

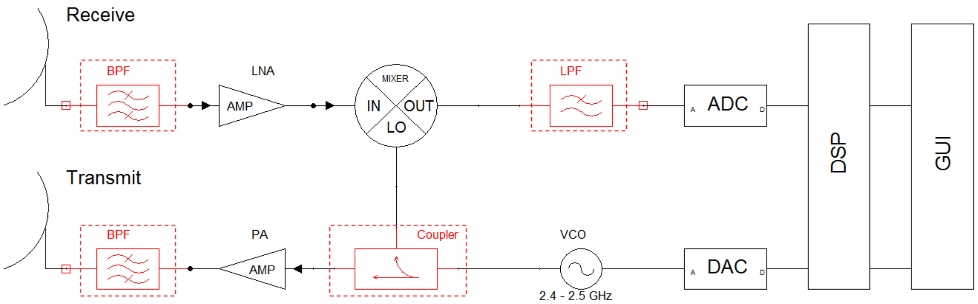

Fig. 1. Radar schematic.

A. Band pass filter

This filter is intended for use at the very end of the transmit path and at the beginning of the receiving path, connected to the antenna. Its purpose in the transmit path is to limit the range of frequencies transmitted. In the receive path it provides protection against potential high power sources at frequencies out of the band of interest.

The systems operating frequency range is the ISM band so the chosen specification for this filter is a band pass from 2.4 to 2.5 GHz. No specification was set for the amount of out-of-band rejection.

B. Coupler

In a FMCW radar, like this one, the receiving signal is mixed with the transmitting signal whose frequency is varies according to a function. The delay in time between a signal transmitted and then reflected will appear as a frequency offset when down converted by a mixer. A coupler is chosen as the element to split the generated signal between the transmit path and the receive path. The initial coupling value requirement was set to be around -10 dB from 2.4 to 2.5 GHz.

C. Low pass filter

The down converted signal, whose frequency is related to the distance to a target, may contain higher undesired frequencies. This occurs because besides the reflection of the desired target, the receiving antenna also captures the reflection of obstacles further away that may not be of interest. These reflections could saturate the analog to digital converter used for signal processing. The group overseeing the system determined initially that a low pass filter with a cutoff frequency of 10 MHz would be enough to visualize our intended targets. No specification was set for the amount of out-of-band rejection.

3. Structures selection and design

The circuit simulator Ansoft Designer was used initially to design the components and to set performance goals for the EM simulations. Microstrip technology was the method of choice for the designs to be considered. This was basically set by the instructor after considering the time available, fabrication facilities options, cost and capabilities of different manufacturing techniques. The actual board material was to be determined. Rogers RO3003 high frequency laminate [3], 30mils thick, was chosen for its low loss properties, familiarity and line width range of the microstrip lines desired. The 50Ω characteristic impedance line was calculated to be 74.1mils wide which is a good width to solder lumped components of package sizes up to 0806 without requiring a wider (capacitive) pad.

A. Band pass filter

The band pass filter design was straightforward with parallel-coupled microstrip lines being selected from the beginning. The main determination to be made was of the order of the filter which is to say, how steep of a rejection would be desired out-of-band. No strict value was set for the out-of-band rejection so a 5^{th} order filter was chosen for presenting better than -20 dB rejection beyond 50 MHz of the pass band.

The lines widths and gaps of the coupled sections were also acceptable as follow: L1,L6=31.2mils; G1,G6=14.9mils; L2,L5=44mils; G2,G5=50.1mils; L3,L4=41.1mils; and G3,G4=71.1mils.

B. Coupler

Initially, coupled microstrip lines as a directional coupler were considered for this component. Unfortunately the gap between the lines for the desired coupling of -10 dB was very narrow. It was less than what's desired considering the processes tolerances. Investigation into a branchline structure yielded a similar issue in which in order to achieve the same coupling, the line width of the higher impedance transformers would be very narrow and below the minimum width desired.

Instead of investigating other types of couplers, and considering that the -10 dB requirement was chosen rather arbitrarily, the design proceeded with two variants. One was a directional coupler with around -13 dB of coupling and the other was a branchline with around -6 dB of coupling. For the directional coupler the coupled lines of width 67.9mils with a gap of 11.4mils yielded good results. For the branchline coupler, good results were found with low impedance transformers width of 91.6mils and high impedance transformers width of 26.4mils.

C. Low pass filter

Initial work was done with stepped impedance lines. Performance was good however the total length was extremely long for the cutoff frequency desired (10 MHz). The design shifted then to using lumped components which have frequency limitations due to reactances of the packaging. At 10 MHz though, these effects can be minimal (by selecting a proper package) and rejection directly above 10 MHz can be well characterized. For higher frequencies only specific rejection bands are of interest. These are the frequency band from which leakage of the RF can occur through the mixer and its harmonics. For this, additional band reject filters (radial stubs) were added with rejection in the band of 2.4 to 2.5 GHz and 4.8 to 5 GHz. The low pass filter part was designed to be of 7^{th} order achieving -30 dB rejection at 15 MHz. The components required were as follow: L1,L4=470nH; C1,C3=470pF; L2,L3=1.5uH; and C2=620pF.

4. EM simulation

The passive components discussed are planar in nature and were great candidates for high frequency simulations using Sonnet which excels in these sorts of designs. The drawing of the structures was performed in a CAD software due to previous familiarity and then imported into Sonnet for simulation. In general the design procedure consisted of the following loop:

1. Simulate structure in Sonnet,
2. Export S-Parameter results to circuit simulator,
3. Identify circuit elements changes that provide same results as obtained,
4. Redraw the circuit with changes that counter the ones identified in step 3 and repeat loop.

Once satisfactory results were obtained the design would be done.

All models were set up to use Sonnet's thick metal model (conductivity=infinite, number of sheets=2, thickness=0.65mils) to better approximate the extra capacitance associated with the thickness of the copper. The default dielectric properties of Rogers RO3003, found in the material library, were used and the models' air layer above the board was set to be 400mils thick.

The characteristics of each component were taken into account when modeling which allowed taking advantage of some features [2] of Sonnet to speed up simulations while maintaining good accuracy. The peculiarities in each of the models are discussed next. Simulation results are presented in the next section compared to measured data.

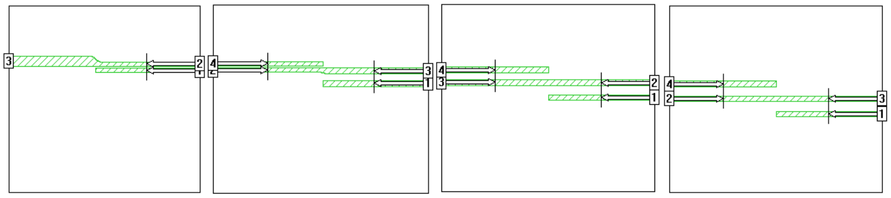

Fig. 2a. Band pass filter models: subdivisions 1(and 7), 2(and 6), 3(and 5), and 4.

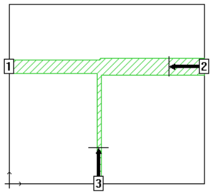

Fig. 2b. Branchline coupler model.

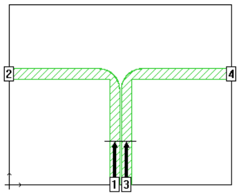

Fig. 2c. Directional coupler model.

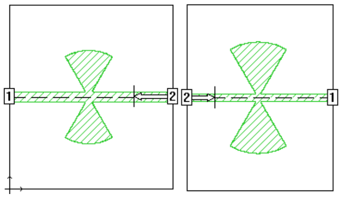

Fig. 2d. Band reject models: subdivisions 1 and 2.

A. Band pass filter

Initial simulations of the whole filter presented the problem of requiring more memory than available. The grid had been set very finely and to reduce the memory requirement an attempt was made to increase the cell size. Even then simulation time was significant for the machine's speed. It was then that a division of the filter was done to solve the filter in a reasonable time without compromise to the grid.

The filter was divided across the center of the coupled lines (Fig. 2a). With this, the problem was divided into 7 subdivisions that could simulate in significantly less time. Further time saving was achieved by taking advantage of the filter symmetry, simulating only 4 out of the 7 subdivisions (3 were identical to others) and manipulating the netlist file used in Sonnet.

Tuning was done by adjusting the lengths of the coupled sections based off of feedback from the circuit simulator as previously described in the general design loop. The widths and gaps of the coupled sections were not adjusted since the circuit simulator microstrip models are accurate for these parameters.

B. Couplers

Both variations of couplers were modeled using the subdivision features and taking advantage of symmetry to minimize the number of subdivisions simulated. This was done so that a finer grid could be used since simulation times of the whole structures were acceptable without subdivision.

The branchline coupler model was reduced to a little more than quarter of its original size (Fig. 2b). The netlist was modified appropriately so that the S-parameters were that of the structure desired. The tuning was done by modifying the lengths of the two different types of quarter-wave transformers.

In the case of the directional coupler the widths and gaps of the coupled lines were set the same as found in the circuit simulator and the model was divided across the center of them (Fig. 2c). Only the length of the coupled sections and feed line bends were tuned. A 90° bend is often a source of extra capacitance which affects the return loss among other parameters and correcting it is important. A fillet radius was found that was neither too capacitive nor too inductive.

C. Low pass filter and band reject

The lower frequency band was not simulated in Sonnet since most features were smaller than the wavelengths around 10 MHz. In order to investigate the higher frequency rejection, simulation was performed from 1 to 7 GHz. The radial stubs used for band rejection were modeled taking advantage of the symmetry along the transmission line. They were also simulated separately (Fig. 2d) so that a finer mesh could be used. This was acceptable since the stubs would be separated far enough for any significant coupling between their fields. Furthermore, the top surface of the simulation boxes was set as free space to prevent glitches in the response at higher order modes cutoff frequencies.

5. Test boards and measurements results

All RF components designed for the course were built on individual test boards so that their performance could be measured and compared with simulation and to determine if they were suitable to be used in the integrated radar board. As indicated before, the boards were made from Rogers RO3003 ½ oz. copper panels. Copper was etched from the top side of the board to form the microstrip patterns and the other side remained untouched serving as ground. Plated via holes were used for ground connections.

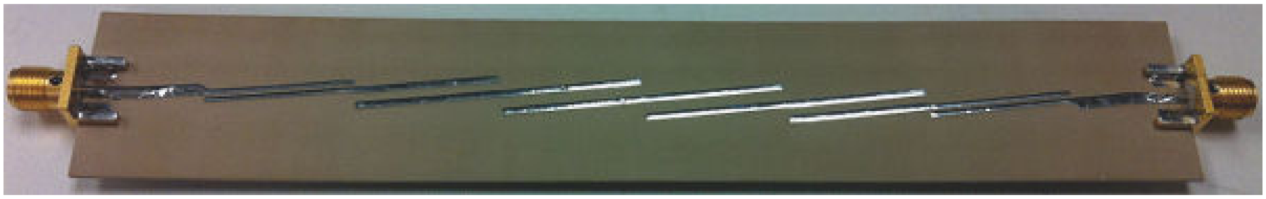

Fig. 3a. Band pass filter test board.

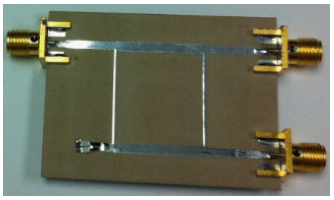

Fig. 3b. Branchline coupler test board.

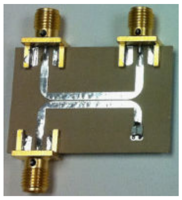

Fig. 3c. Directional coupler test board.

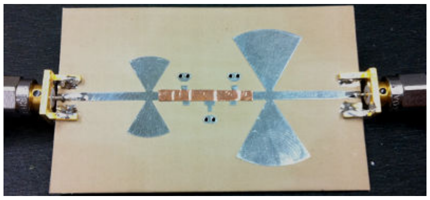

Fig. 3d. Band reject test board.

A. Band pass filter

The measured performance of the filter (Fig. 3a) can be seen in Fig. 4a. The general shape of the return loss plot is as expected. It does however show a shift in the rejection at the lower end of the pass band. In addition, the insertion loss at the center frequency is significantly larger than simulated. Although the simulated model used a perfect conductor, the difference in insertion loss (more than 4 dB) is beyond the expected conductor losses plus losses of the connectors (included in the measurement).

When investigating the cause of the discrepancy, one simulation setting that had an affect was that of the top plane of the simulation box. When setting it to free-space, instead of metal as was used during design, a similar shift was observed in the rejection at the lower end of the pass band. Degradation in the insertion loss was also noticed. The magnitudes of the shift and increased insertion loss did not totally match what was measured though. It seems obvious that radiation accounts for good part of the discrepancy observed, and possibly additional factors were also involved such as manufacturing tolerances, material property variation and return loss of connectors interface.

B. Couplers

Fig. 4b and 4c show the performance of the branchline (Fig. 3b) and directional coupler (Fig. 3c) respectively. The insertion losses associated with the through and coupled paths are seen to be very close to simulation in both cases. In the case of the directional coupler the measured insertion loss of the coupled path is slightly less than simulated and indicates that it's a little over coupled. The return losses are worse than simulated but still acceptable (under -15 dB). The connectors could be responsible.

C. Band reject

Unfortunately the lumped components necessary for the low pass filter performance were not ordered in time and were not used. As can be seen in Fig. 3d, the low pass circuitry was bypassed with a copper tape to measure the higher frequencies rejection properties. Fig. 4d shows the high frequencies rejection of the board. In the insertion loss trace the bands from 2.4 to 2.5 GHz and 4.8 to 5 GHz show proper suppression, comparable to simulation. Performance out of these bands was not of interest.

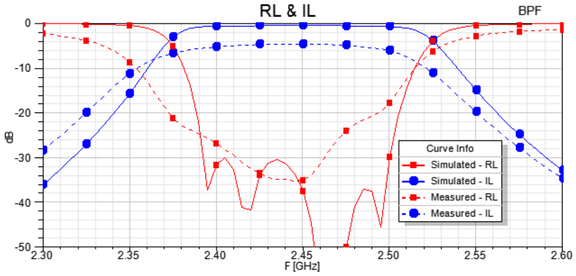

Fig. 4a. Band pass filter – simulated vs. measured comparison.

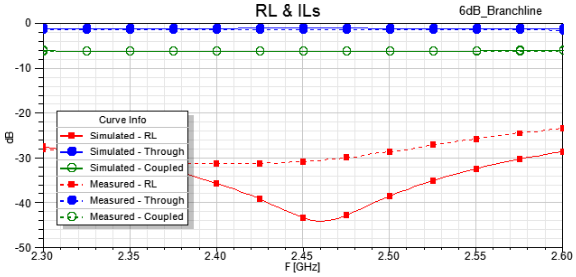

Fig. 4b. Branchline coupler – simulated vs. measured comparison.

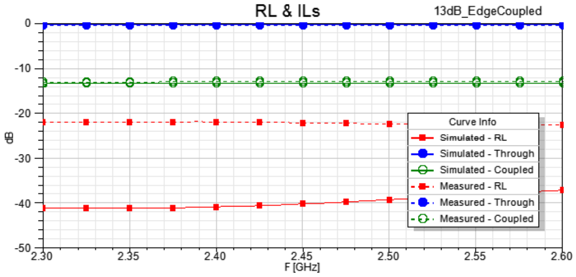

Fig. 4c. Directional coupler – simulated vs. measured comparison.

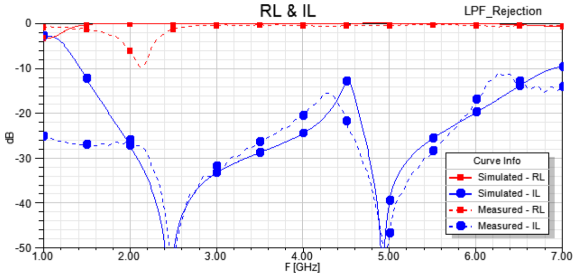

Fig. 4d. Band reject – simulated vs. measured comparison.

6. Conclusions

The components described here performed as expected and each one of them met their individual specified goals. The results were very satisfactory considering that the measurements were from the only prototypes built. The performance comparison between EM simulations and measured data attests to the effectiveness of the process / software chosen. Unfortunately the available time did not allow for a redesign of the band pass filter, whose performance could've been improved.

The branchline coupler and the filters were included in the integrated radar layout. The band pass filter, however, was bypassed during actual tests of the radar since the antennas used already provided rejection out of the radar band. The system eventually was successfully tested with a mix of designed parts (such as the passive RF components) and off-the-shelf components.

Acknowledgments

I'd like to acknowledge the efforts of the instructor Dr. Serhend Arvas for being available to students, providing guidance in the design of a broad selection of components and coming up with the course's concept. The following companies directly influenced the work presented herein: Anaren Microwave, Inc. which provided RF components and materials, and funded my tuition for the course; Rogers Corp which provided sample high frequency laminates; and Sonnet Software which was gracious to provide a fully functional trial version of Sonnet for the duration of the course.

References

[1] D. M. Pozar, *Microwave Engineering*, Wiley, 3rd edition, Feb. 2004.
[2] Sonnet Software, Inc., "*Sonnet User's Guide v13*", http://www.sonnetsoftware.com, Jun. 2011.
[3] Rogers Corp., "*RO3000® Series High Frequency Laminates*", Publication #92-130, http://www.rogerscorp.com, Dec. 2010.
[4] D. Ryan, *"MIT Lincoln Laboratory researchers introduce students to radar engineering"*, http://www.ll.mit.edu/news/iapradarcourse.html, Inst. of Technology Lincoln Laboratory, Apr. 2011.