Design for MOSIS Educational Program (Research)

Project report of 69094

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In the report, one conference paper is first given. Following some test results and also some explanation are given to address the problems.

The conference paper is:
“3-22GHz CMOS distributed single-balanced mixer”, IEEE International System on Chip Conference, 2004.

3-22GHz CMOS Distributed Single-Balanced Mixer

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Abstract

This paper presents a novel 5 stage CMOS distributed single-balanced mixer (DMIXER). The on-chip transmission lines are used to connect the RF and LO parts of the mixer. The distributed mixer is designed in standard 0.18µm CMOS technology. It achieves 3.8dB average conversion gain from 3GHz to 22GHz, operates from 1.2V power supply, dissipates 129.36mW, among which 36mW is consumed by distributed active balun, and occupies 3.02 mm^2 silicon areas.

Introduction

The increasing bandwidth demands in broadband system and wireless communication system push the integrated circuits operating at higher frequencies. CMOS technology has attracted low-cost advantage compared with other technologies. Nevertheless, the CMOS technology has lower f_T and larger parasitic capacitance which makes CMOS circuits difficult to work in very high frequency. New circuit typologies are needed.

As a good choice for high frequency applications, many CMOS distributed circuits have been reported [1]. CMOS distributed circuits were first explored with distributed amplifier. With the proper designed transmission lines in the gate-line and drain-line, the parasitic capacitances of the transistors are absorbed and different signals through different paths are added in phase at tap points of the circuits which leads to the extension of the bandwidth. In CMOS distributed amplifier circuits, the transmissions line can be implemented with the artificial line (formed with lumped inductors and capacitors) [2] [3] [4] and the real transmission line [5]. Besides the distributed amplifier, other distributed circuits were also explored. By connecting the output of the distributed amplifier back to the input, the distributed Voltage-Controlled Oscillators were implemented [5] [6].

The mixer is a very important component in broadband system and wireless communication system. Different distributed mixers have been explored in microwave area. Compared with the passive mixer, the active mixer can have the positive conversion gain. The single gate mixer and dual gate transistor mixer have worse isolation compared with single balanced mixer and double balanced mixer. The double balanced miser has more power consumption compared with the single balanced mixer. The distributed single balanced mixer was reported with microwave circuits in [7]. The distributed single balanced mixer designed with the real transmission line is explored with CMOS technology in this paper. The design and analysis of the distributed mixer is presented.

Transmission line design

The transmission line design is very important for the distributed circuit design. Artificial transmission lines with lumped inductors and capacitors are not suitable when the operating frequency approaches the self-resonance frequency of the on-chip inductors [6]. Compared with the artificial line, the real transmission line doesn't have accurate and easily used model. The EM simulation software is needed for the transmission line design.

6 metals layers are available in 0.18µm CMOS technology. The thicker metal 6 reduces the loss of the transmission line and the large distance from metal 6 to the substrate reduces the loss from substrate coupling.

Compared with the microstrip transmission line, the coplanar stripline has larger characteristic impedance. In our design, the coplanar stripline is chosen and its structure is shown in Fig. 1.

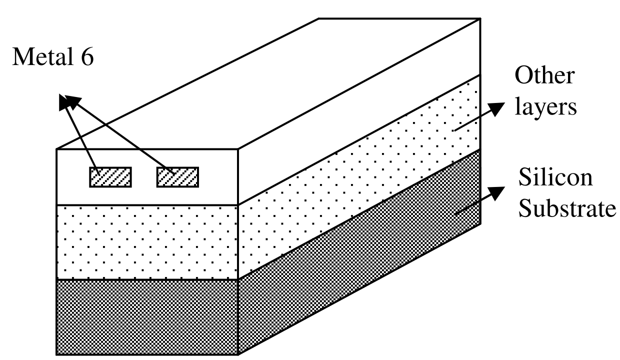

Fig. 1. The coplanar stripline structure

Through the simulation with IE3D, the characteristic impedance of the transmission line is shown in Fig.2.

According to Fig. 2, the characteristic impedance of the transmission line increases with the increasing of the spacing and the reduction of the width of the coplanar stripline.

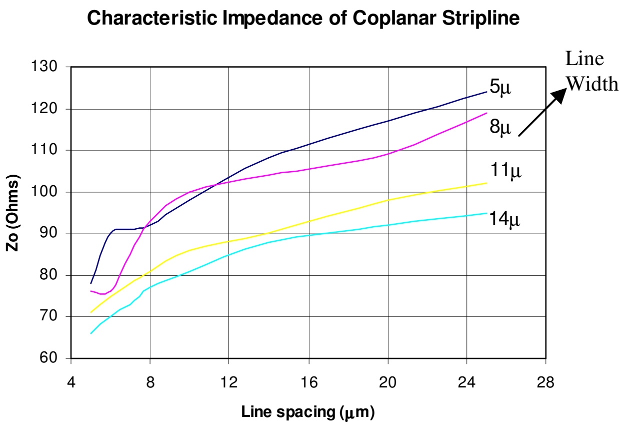

Fig. 2. Characteristic impedance of the coplanar stripline versus the width and spacing of the transmission line.

Proposed distributed mixer

The structure of the 5 stage CMOS distributed single balanced mixer is shown in Fig. 3. The unit cell of the distributed mixer is a single balanced mixer. The input and output of each unit mixer are connected with the transmission lines, TRF, TLO+, TLO-, TIF+, and TIF-.

The mixer in this work down converts the RF signal (3-22GHz) to fixed 500MHz IF signal with a varied frequency LO signal.

The impedance matching and phase synchronization are two important considerations in distributed circuit design.

A. Impedance matching

The inputs of the distributed mixer are one RF signal and two differential LO signals. They are connected through the transmission lines TRF, TLO+ and TLO- in Fig. 3. The input impedance matching is a broadband matching (3-22GHz in this work). The outputs are two differential IF signals. They are connected through the transmission lines TIF+ and TIF- as in Fig. 3. The output impedance matching is a narrowband matching (500MHz in this work).

For an ideal transmission line, the characteristic impedance Z_0 is calculated as equation (1).

$$Z_0 = \sqrt{L_u / C_u} \tag{1}$$

L_u and C_u are the unit inductance and unit capacitance of the transmission line.

For the inputs of the distributed mixer, the transmission lines are period loaded by the input parasitic capacitances of the transistors (C_{gs}). The loaded input impedance Z' of the transmission line with the load capacitor is calculated as equation (2).

$$Z' = \sqrt{\frac{jwL_g + R_g}{jw(C_g + \frac{C_{gs}}{L_g}) + G_g}} \tag{2}$$

L_g and R_g are the series inductance and resistance of the transmission line per unit length. C_g and G_g are parallel capacitance and conductance of the transmission line per unit length. C_{gs} is the input parasitic capacitance of the transistor.

According to equation (1) and (2), the characteristic impedance of the loaded transmission line is less than that of the unloaded transmission line. To match the input impedance of the mixer to 50Ω, the characteristic impedance of the unloaded transmission line is designed higher than 50Ω. After loaded by the parasitic capacitors, the characteristic impedance of the transmission line is 50Ω.

B. Phase synchronization

Another important consideration in the distributed mixer design is phase synchronization. The distributed mixer has several signal paths from the input to the output. The signals through different signal paths need to have the same phase shift and need to be added in phase at the tapping point of the distributed circuits so that the signal at the output is amplified.

The voltage at the kth tap of the transmission line is

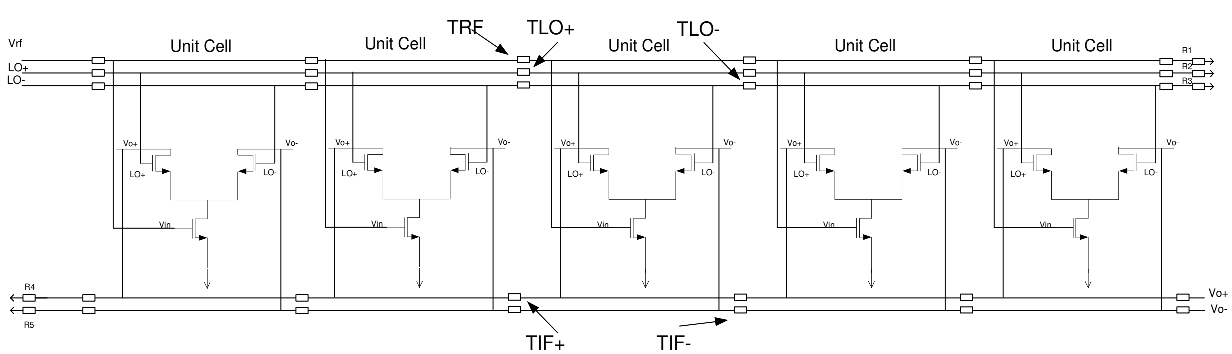

Fig. 3. CMOS distributed Single-balanced mixer

related to the transmission line's segment length l_g and complex propagation constant of the loaded transmission line [6].

The RF signal at kth tap is expressed as equation (3).

$$V_{gRF\_K} = V_{RF} e^{-(k-1/2)\gamma_{RF} l_{RF}} \quad (3)$$

The LO signal at kth tap is expressed as equation (4).

$$V_{gLO\_K} = V_{LO} e^{-(k-1/2)\gamma_{LO} l_{LO}} \quad (4)$$

Based on the single-balanced mixer theory, the IF signal at kth tap is calculated as equation (5).

$$\begin{aligned} V_{dIF\_K} &= \frac{Z_d}{2} \circ G_c \circ V_{gRF\_K} \circ V_{gLO\_K} \\ &= \frac{Z_d}{2} \circ V_{RF} \circ V_{LO} \circ G_c e^{-(k-1/2)(\gamma_{RF} l_{RF} - \gamma_{LO} l_{LO})} \end{aligned} \quad (5)$$

G_c is the single stage mixer conversion transconductance and $G_c = \frac{2g_m}{\pi}$. Z_d is the characteristic impedance of the output transmission line.

The signal at the output of the mixer is calculated as equation (6).

$$\begin{aligned} V_{IF\_OUT} &= V_{IF+\_OUT} - V_{IF-\_OUT} = 2\sum_{k=1}^{n} V_{dIF\_K} e^{-(n-k+1/2)\gamma_{IF} l_{IF}} \\ &= 2\sum_{k=1}^{n} \frac{Z_d}{2} \circ V_{RF} \circ V_{LO} \circ G_c \circ e^{-(k-1/2)(\gamma_{RF} l_{RF} - \gamma_{LO} l_{LO})} e^{-(n-k+1/2)\gamma_{IF} l_{IF}} \\ &= Z_d \circ V_{RF} \circ V_{LO} \circ G_c \circ e^{-(\gamma_{RF} l_{RF} - \gamma_{LO} l_{LO} - \gamma_{IF} l_{IF})} \frac{e^{-n\gamma_{IF} l_{IF}} - e^{-n(\gamma_{RF} l_{RF} - \gamma_{LO} l_{LO})}}{e^{-\gamma_{IF} l_{IF}} - e^{-(\gamma_{RF} l_{RF} - \gamma_{LO} l_{LO})}} \end{aligned} \quad (6)$$

In the special case when the output impedance is matched to Z_d and the equation (7) is satisfied.

$$\gamma_{RF} l_{RF} - \gamma_{LO} l_{LO} = \gamma_{IF} l_{IF} = \gamma l \quad (7)$$

We can get the final mixer output as equation (8)

$$V_{IF\_OUT} = n Z_d V_{RF} V_{LO} G_c e^{-n\gamma l} \quad (8)$$

According to the equation (6) and (8), we can see that although each single stage signal output voltage is small, the total mixer output signal voltage can be larger.

In a single frequency, the equation (7) can be easily satisfied by using different line widths and lengths of the transmission lines. For a broadband frequency, the equation (7) is difficult to be satisfied, because there are three variables in the equation. Since the IF frequency is much less than the RF and LO frequencies, with the same transmission line length, the phase shift through the IF transmission line is much less than those of RF and LO lines. Based on the reason above, the phase shift through the IF transmission line is ignored. In this work the IF signal is just shorted, that means the zero phase shift through the IF transmission line. The equation (7) changes to equation (9) based on that condition.

$$\gamma_{RF} l_{RF} = \gamma_{LO} l_{LO} = \gamma l \quad (9)$$

The equations (9) can be easily satisfied.

Distributed Active balun

The distributed mixer shown in Fig. 3 needs one RF signal and two differential LO signals. To avoid the broadband transformer needed off-chip, the distributed active balun is designed to implement broadband conversion of LO signal. Its structure is shown in Fig. 4.

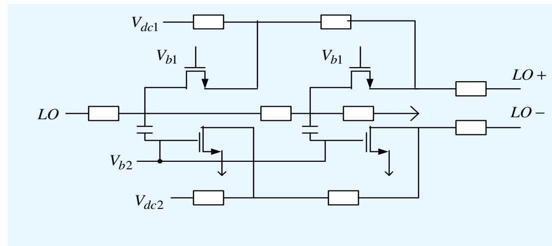

Fig. 4. Distributed active balun

The common source and common gate structure are used to generate differential signals with 180^0 phase difference. It has 2~3 dBm LO signal loss.

The final structure of the mixer is shown in Fig. 5.

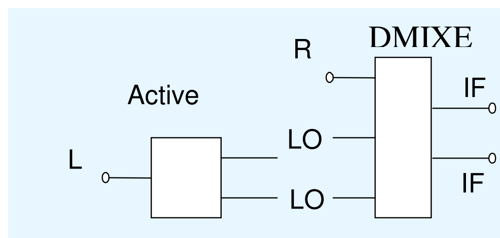

Fig. 5. Distributed mixer topology

Simulation results

The design and simulation procedure is described as follows: First, the S-parameter files of the transmission lines are gotten through the simulation using IE3D software. Second, the S-parameter files are imported into HP-ADS. Finally, The DC and harmonic balance simulations with HP-ADS are done to get the conversion gain, S-parameter response and noise performance of the mixer. The conversion gain is shown in Fig. 6.

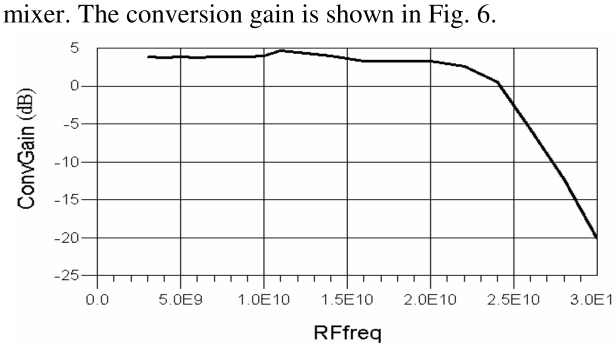

Fig. 6. Conversion gain of the mixer

The DMIXER operates from 1.2V power supply and consumes 129.36mW, among which 36mW is consumed by the distributed active balun. The mixer down converters the RF signal (3GHz~22GHz) to a fixed 500MHz IF signal through a varied frequency LO signal. The DMIXER shows 3.8dB average conversion gain from 3GHz to 22GHz. The S-parameter performance is shown in Fig. 7. The S11 of the DMIXER is less than –10dB from 3GHz to 22GHz. The S33 of the DMIXER is less than -10dB at 500MHz. The noise performance of the DMIXER is shown in Fig. 8.

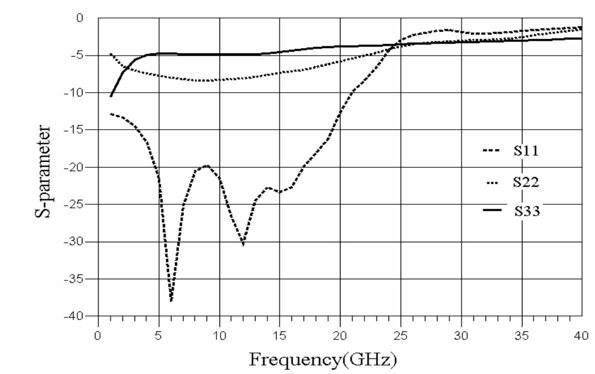

Fig. 7. S-parameter of the mixer

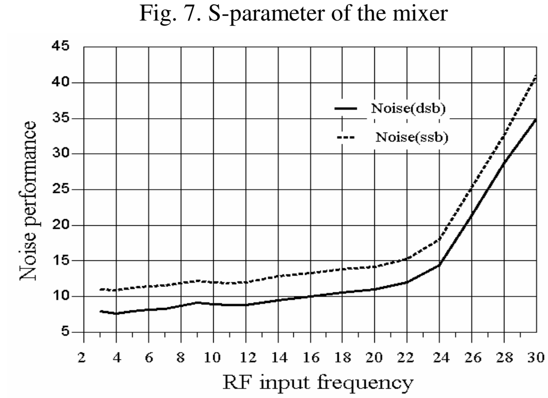

Fig. 8. Noise performance of the mixer

The layout of the distributed mixer is shown in Fig. 9. The chip will be tested with on chip probe to avoid the influence from the package and the bonding wire.

Conclusion

In this paper, the novel distributed mixer has been introduced. Distributed technique is effectively used to extend the bandwidth of the mixer. The analysis of distributed mixer is presented. The distributed active balun is implemented to achieve the broadband single ended signal to differential signal conversion. The distributed mixer achieves a 3.8dB average conversion gain through 3-22GHz frequency region.

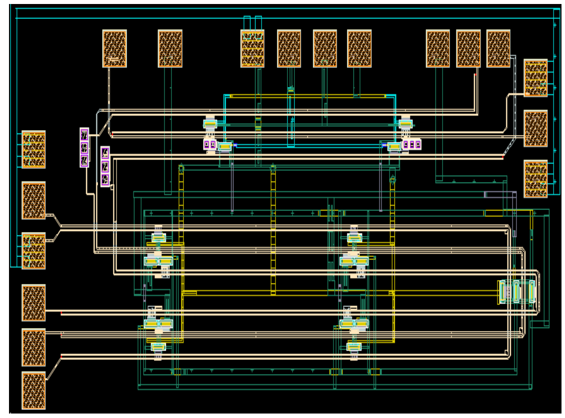

Fig. 9. Distributed mixer layout

Acknowledgement

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Testing results:

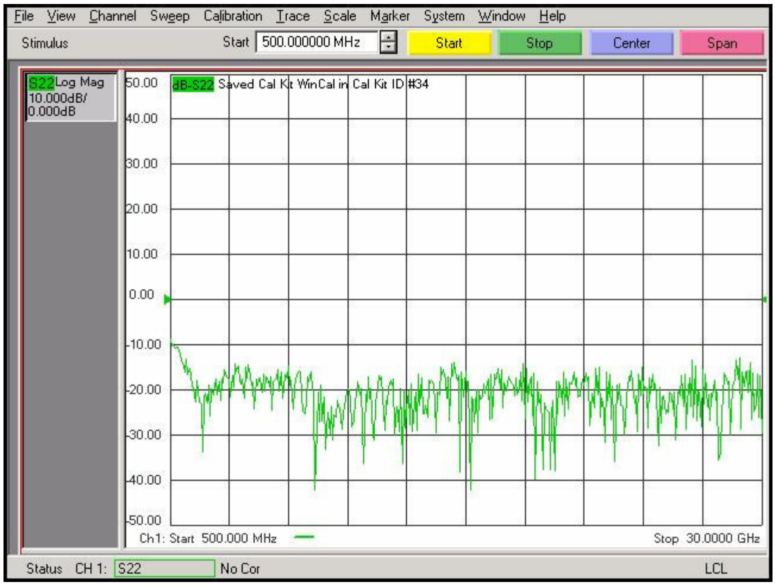

Figure Input impedance matching of RF

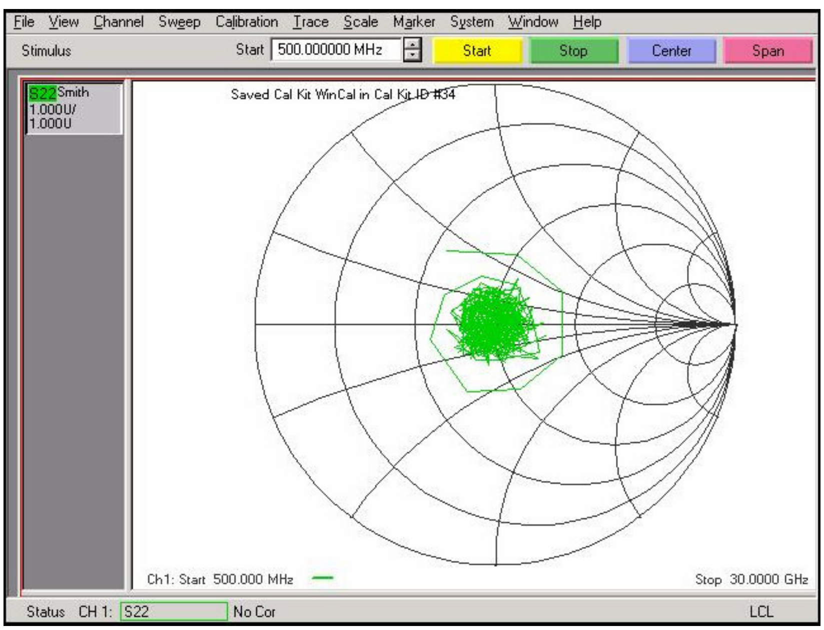

Figure Smith chart of input impedance matching of RF

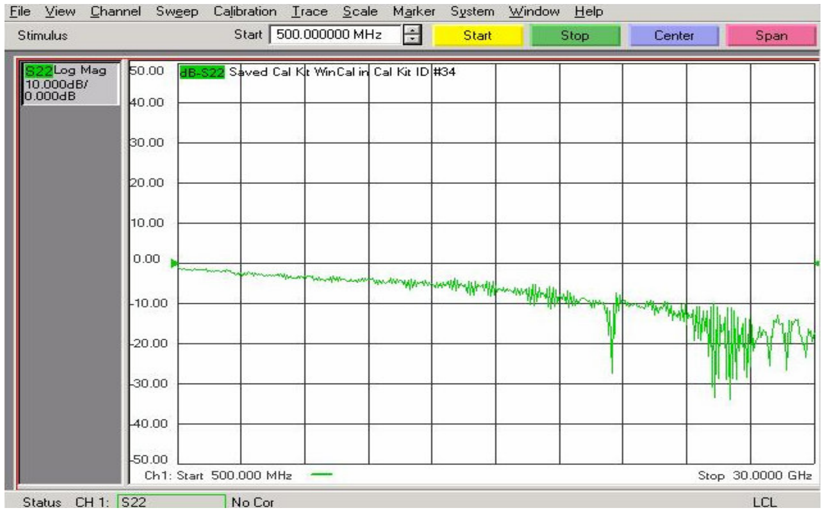

Figure. Input impedance matching of LO

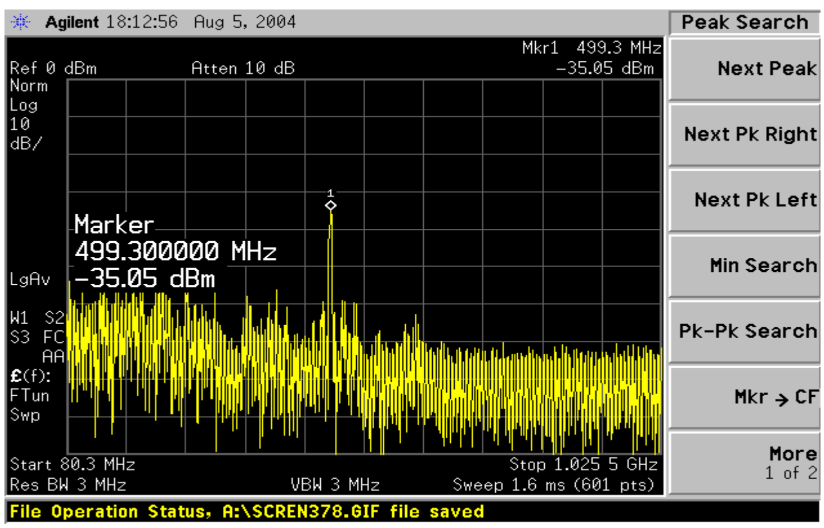

Figure. The output spectrum with 8GHz input and LO with 8.5GHz

The mixer functions as a down converter. With -10dbm input, and around 9dB loss of the wire and the passive component, the mixer shows -10dB conversion gain which is different from the expected.

The reason of that lies below:

1). Incomplete parameter of the process. This design heavily relies on the transmission line design, and the transmission line needs the accurate parameter. The transmission line model is not accurate, which cause the signal phase through different path not same.

2). The packaged chip with on chip probe testing is used in this design. The bonding wire in the layout blocks the probe which need to access the probe pad.