Multiplexer Design for the BASS Rake Acoustic Transducer Array

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Abstract - **The BASS Rake is an acoustic current meter designed to measure velocity profiles through the continental shelf wave bottom boundary layer. The instrument uses BASS electronics with a new transducer geometry to resolve the primary spatial and temporal flow scales of the wave boundary layer. The necessary characteristics of an interface satisfying the requirements of both the BASS transmit/receive circuit and the BASS Rake sensor design are extremely low through resistance, $O(1\,\Omega)$, rapid switching, $O(10\,\mu s)$, flexible cross connection of the transducers, and strong isolation between channels, $> 40\,dB$. The layered multiplexer described here is designed to meet these requirements.**

I. INTRODUCTION

Surface swell over the continental shelf generates a thin sheet of oscillatory shear flow called the wave bottom boundary layer. Large bottom stresses generated by the layer are an important element of the sediment entrainment and transport process. Additionally, high levels of turbulent dissipation within the layer have a strong effect on the mean flow over the continental margins. The thickness of the layer is of order $1\,cm$, making this a technically challenging region to instrument [1, 2, 4].

The BASS Rake, an instrument currently under development at the Woods Hole Oceanographic Institution, is an acoustic current meter designed to record the detailed dynamic structure of the continental shelf wave bottom boundary layer. A discussion of the characteristic scales of the wave boundary layer and the design of the BASS Rake current sensor can be found in [5]. The new sensor is based on the BASS differential travel time technique and uses the BASS electronics package [6]. The design of the new sensor requires a flexible interface between the BASS transmit/receive (T/R) circuit and the BASS Rake acoustic transducer array. The sensitivity of the BASS velocity measurement to the nature of the connection between the T/R circuit and the transducers [6] makes the design of the interface nontrivial.

This paper documents the development of a layered multiplexer interface that provides the flexibility required by the BASS Rake measurements with an acceptably small effect on the existing T/R circuit. The characteristics of both the T/R circuit and the sensor that are relevant to the interface design are presented in Section II. Sections III and IV describe the design process leading to the layered multiplexer and the multiplexer itself. The results are summarized in Section V.

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II. CIRCUIT AND SENSOR REQUIREMENTS

The sensor array consists of 192 acoustic transducers mounted on four tines. Pairs of transducers on opposing tines define velocity measurement paths. There are 96 horizontal paths crossing in pairs to determine the horizontal velocity vector at 48 levels above the bottom. 38 levels are concentrated in the bottom $3.7\,cm$ with $1\,mm$ vertical spacing. An additional 10 levels are logarithmically spaced from $4\,cm$ to $30\,cm$ above the bottom. Vertical velocities are measured by selecting transducers on opposing tines and at different heights. The mainlobe of the acoustic signal is sufficiently wide to permit several layers of vertical separation in the dense portion of the array [5].

In BASS, a T/R circuit is hardwired to a fixed pair of transducers. It is absolutely necessary for the accuracy of the velocity measurement that both of the transducers defining an acoustic path be connected to the same T/R circuit [6]. Hardwiring the BASS Rake in this manner would have the advantage of requiring very few modifications to existing hardware and software. Most of the changes would be associated with an extended addressing scheme to accomodate a four fold increase in the number of acoustic paths compared to a standard BASS instrument. Unfortunately, that increase would also require an increase in the number of T/R circuits. Four independently selectable T/R circuits are assembled on a single T/R board. The boards are expensive and would occupy rack space necessitating a longer and more expensive pressure housing. The monetary costs would not be insubstantial. More importantly, there would be scientific costs associated with this approach. Each measurement of vertical velocity would sacrifice two of the horizontal measurement levels. Moreover, changing the location of vertical measurements could not be accomplished in software but would require changes to the wiring harness. A flexible response to different deployment scenarios would no longer be possible.

A multiplexer interface that could select the useful transducer pairs from opposing tines and connect the pair to the same T/R circuit would make a full suite of velocity measurements possible. Potentially the array could be driven from a single T/R circuit. However, depending on the nature of the switching elements in the interface, this arrangement might present a prohibitive capacitive shunt load to the signal. That shunt load could be reduced, at the expense of some measurement flexibility, if each of the 4 T/R circuits on a T/R board was multiplexed to the 24 odd or even transducer pairs on opposing tines.

The number of T/R circuits used would reflect a balance between signal loading and measurement flexibility. Multiplexing to the T/R circuits as well as the transducers would trade an increase in shunt load for restored flexibility. Note that multiplexing has the potential to reduce the number of T/R boards from 24, required to hardwire the transducers, to perhaps 1 or 2. This would be a considerable savings in both expense and rack space that could be applied to the multiplexer.

The ability to satisfy the scientific requirements makes this an attractive approach, but the differential travel time measurement imposes several significant constraints on the electrical characteristics of any interface between the T/R circuit and the transducer. In particular, the BASS velocity measurement is sensitive to variations in the equivalent capacitance of the interface, the transmission lines, and the transducer electrodes. The sensitivity has been reduced by minimizing the source and load impedances of the T/R circuit. Both impedances are approximately $10\,\Omega$ [6]. It is imperative that this value not be increased significantly. The through impedance of a multiplex interface should be of order $1\,\Omega$ or less.

A further constraint is switching speed. For a $15\,cm$ path length a velocity measurement along a single acoustic path requires $320\,\mu s$. The forward and reversed acoustic propagation time is $220\,\mu s$ and $100\,\mu s$ is needed for processing and switching overhead [6]. To record a complete velocity profile in an acceptable sample window of $30\,ms$ to $50\,ms$ [5] requires an interface that can change state well within the overhead period. A switching time of order $10\,\mu s$ is indicated.

Finally, the interface should reduce cross talk between channels. BASS channels are well isolated by separate T/R circuits, a coaxial harness, and the geometry of the acoustic paths [6]. A multiplex interface in the BASS Rake would share T/R circuits between many channels. The small cross sectional area of the tines makes the use of coaxial cable problematic and contributes to capacitive coupling between densely packed signal wires. The wide mainlobes and the geometry of the tines encourage acoustic coupling between the channels. The combination of capacitive and acoustic coupling would contaminate the velocity measurement of one path with velocities from other paths. An average velocity with weights determined by the degree of coupling would result. A measurement accuracy of 10% requires $30\,dB$ to $40\,dB$ of isolation between channels.

III. INTERFACE DESIGN

Meeting the interface specifications discussed above depends, obviously, on the switching elements chosen to multiplex the signals. Mechanical switches, such as reed relays, have the advantages of effectively zero on resistance and negligibly small series and shunt capacitances, typically $<1\,pF$. However, the duration of contact bounce in a reed switch is of order $10\,ms$. That is three orders of magnitude above the switching speed specification and amply sufficient to disqualify mechanical relays from further consideration. Some form of electronic switch with fast switching and extremely low through resistance is required.

Packaged arrays of "low resistance" electronic switches have $R(on)$ values in the range $20\,\Omega \leq R(on) \leq 100\,\Omega$, far too large for this application. However, specialty MOSFETs are currently available with drain-source on resistances below $1\,\Omega$. The VN3205 N-Channel Enhancement Mode Vertical DMOS FET (Supertex, Inc.©), with $R_{DS}(on) = 0.3\,\Omega$, has been chosen for this project. This is acceptably small compared to the source and load impedances of the T/R circuit. Further, the VN3205 turns on in less than $25\,ns$ and off in less than $50\,ns$, nearly three orders of magnitude faster than the specification. These are promising qualities for the multiplexer, but there are other characteristics of the VN3205 (or any MOSFET) that make their use in this situation more complicated than treatment as ideal switches. It may be helpful to refer to Figure 1 during the following discussion.

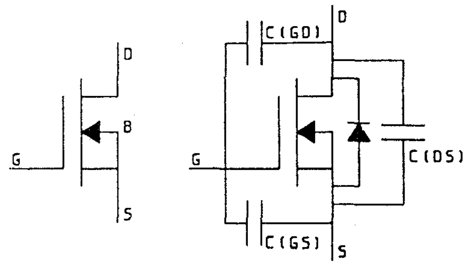

Figure 1. VN3205 N-Channel Enhancement Mode Vertical DMOS FET - A schematic representation of the device is shown on the left with the gate, drain, source, and body/substrate appropriately labeled. On the right a model of the electrical characteristics of the VN3205 is shown. The capacitances are related to the geometry of the gate, drain, and source regions on the silicon substrate. The nominal (maximum) values are: C_{DS}=50 (100) pF, C_{GD}=20 (30) pF, and C_{GS}=200 (270) pF. The diode is formed by the n-type channel region, which is in contact with the drain, and the p-type body, which is internally connected to the source terminal.

As shown in Figure 1, there is capacitive coupling between each of the terminals. This is a result of the size, shape, and proximity of the gate, drain, and source regions on the silicon substrate of the transistor. The nominal (maximum) values are: $C_{DS} = 50\ (100)\,pF$, C_{GD}=20 (30) pF, and C_{GS}=200 (270) pF. These values are high compared to MOSFETs with larger $R_{DS}(on)$. Relatively high capacitance is one of the performance costs associated with reduction of the on resistance. The drain-source diode is formed by the n-type channel region, which is in contact with the drain, and the p-type body, which is internally connected to the source terminal in virtually all currently available MOSFETS. The stray capacitances and the diode complicate the interface design in several ways.

The first difficulty is feedthrough coupling of the signal by the drain-source capacitance. The transmitter signal sent to the transducer is a $1.75\,MHz$ burst at $\pm 5\,V$. The received signal sent from the transducer to the receiver is also bipolar but only a few tenths of a volt or less in amplitude. The gate voltage is $\pm 12\,V$. When the FET is on, the low value of $R_{DS}(on)$ effectively shorts C_{DS} and it can be ignored. In the off state, however, the

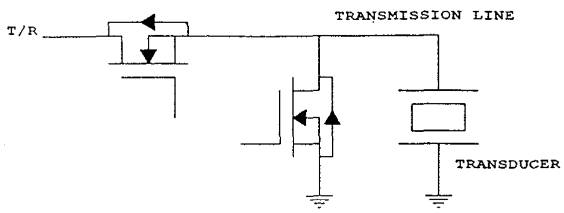

Figure 2. FET SHUNT SWITCH - The series and shunt FETs are operated in opposite states. The shunt switch is used to eliminate capacitive feedthrough coupling when the series switch is open. It has the added benefit of strongly reducing acoustic coupling by connecting the signal terminal of the deselected transducer to ground through the transmission line.

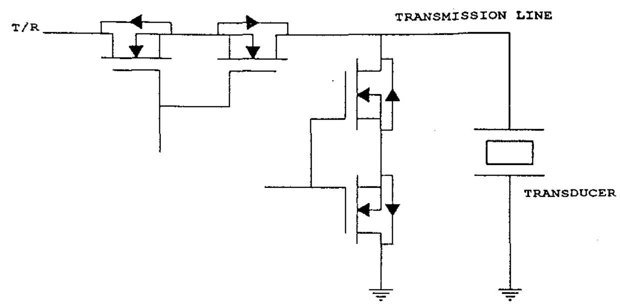

Figure 3. QUAD FET L-SECTION - The shunt and series portions of the L-section are each composed of two FETs connected source to source. This arrangement prevents halfwave rectification of the signal by the drain-source diode of the "open" branch of the L.

drain-source capacitance makes the "open" switch look like a mere $1\,K\Omega$ to $2\,K\Omega$, rather than the $10^4\,M\Omega$, or more, one would expect for $R_{DS}(off)$. C_{DS} couples the $1.75\,MHz$ transmitter signal intended for the selected channel through to the deselected transducers. These transducers broadcast signals, which are received by the other end of the selected channel. The acoustic signals are also received by other deselected channels and coupled through each C_{DS} to the receiver. In all cases the chosen velocity signal is contaminated by velocities from other levels of the boundary layer.

A shunt FET, as shown in Figure 2, is a common and attractive way to eliminate the feedthrough coupling [3]. When the series FET is on, selecting that transducer for use, the shunt is turned off. The series $R_{DS}(on)$ and the shunt C_{DS} then form a voltage divider with entirely negligible, $< 0.1\,\%$, signal attenuation. The relatively high impedance of the shunt makes it effectively invisible. When the transducer is deselected the situation is reversed. The series FET is off and the shunt FET is on, essentially shorting the capacitive feedthrough signal to ground. In this state the shunt has the added and highly desirable effect of strongly reducing acoustic cross talk by connecting the signal terminal of the deselected transducer to ground through the transmission line.

Shorting the deselected channels to ground in this manner is a potent technique for cross talk reduction, particularly given the mechanical design of the BASS Rake. The small cross sectional area of the tines limits the outside diameter of the transmission lines to less than $0.5\,mm$. Single conductor, shielded biomedical specialty wire can be found in this size range if the outer jacket is removed. However, the exceedingly fragile nature of the #38 stranded center conductor makes a physically more robust signal line desirable. Conformally coated transformer wire has very satisfactory size and strength characteristics, but capacitive coupling between the tightly packed and unshielded wires would preclude their use if it was permitted to occur. Additionally, as previously discussed, the geometry of the acoustic paths in the BASS Rake intentionally invites acoustic coupling. The shunt FET has proven extremely effective at reducing signal coupling caused by C_{DS} leakage, transmission line coupling, and spurious acoustic pickup. A prototype BASS Rake using unshielded wire for the transmission line and a single stage VN3205 series-shunt L-section has demonstrated total cross talk reduction of $25\,dB$ to $30\,dB$.

It should be noted that electronic switches are often arranged in T or π-sections, rather than an L, to achieve good isolation. There is no advantage to such an arrangement here for two reasons. First, the hard ground of the transmission line and transducer provided by the shunt is highly advantageous for cross talk reduction and would be lost with a T-section. Second, C_{DS} is approximately equal to the capacitance of the transducer, so the additional FET would increase signal loading with only a small gain in isolation. The L-section is a better choice in this situation.

The shunt FET reduces cross talk to negligible levels, but it creates another serious problem. In the deselected state the shunt diode conducts whenever the bipolar transmitted signal is more than a diode drop negative, clipping that portion of the signal to ground. The series diode behaves similarly in the deselected state. The result is half wave rectification of every burst transmitted. A solution is shown in Figure 3. A second FET is added to each branch of the L-section and connected source to source. This places the diodes of each branch in series with opposite polarity and eliminates the rectification. The change doubles $R_{DS}(on)$ to $0.6\,\Omega$, but this is still within acceptable limits.

The final complication associated with the stray capacitances is signal loading. Each L-section has an equivalent capacitance shunting the signal line to ground. The capacitances of each switch section multiplexing a T/R circuit to a suite of transducers are in parallel and therefore combine additively. Each T/R circuit will be used to drive 48 transducers if a single T/R board is used. With 24 L-sections connected to each of the two T/R circuit signal lines (the signal lines are multiplexed to opposite ends of the selected acoustic axis) the equivalent impedance seen by the receiving transducer is comparable to the receiver impedance it is trying to drive. The equivalent impedance seen by the transmitter is considerably smaller than the transducer impedance. In both cases performance is seriously degraded. Using additional T/R boards to decrease the load on each circuit is undesirable due to the loss of measurement flexibility. A multiplexer configuration that can hide most of the stray

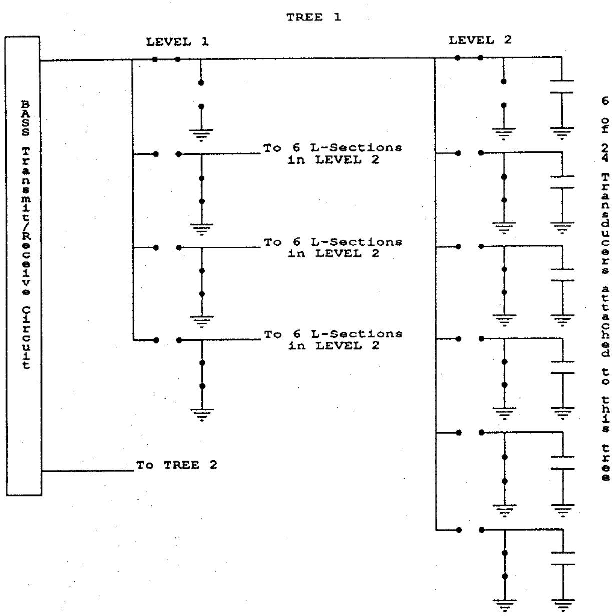

Figure 4. TWO LAYER MULTIPLEXER - The tree structure hides a portion of the capacitive shunt load behind deselected L-sections. The arrangement shown is optimal for a single T/R board. The FET L-sections are drawn as a pairs of switches and only a portion of the first tree is shown for simplicity. The upper L-sections in each level of the first tree are selected. One L-section in each level of the second tree, not shown, is also selected. All other L-sections in both trees are deselected.

capacitance from the selected signal line is required.

IV. THE LAYERED MULTIPLEXER

A major portion of the stray load can be hidden by adding layers to the multiplexer in a branching tree structure as shown schematically in Figure 4. It can be shown that there is a configuration that maximizes the shunt impedance of the multiplexer subject to constraints on measurement flexibility, number of FETs used, and switching speed of the tree. The tree works by hiding some of the load behind deselected L-sections in each layer. The shunt switch of a deselected L-section grounds the input to the remainder of that branch eliminating further contribution to the load. In the two layer tree shown only the two selected L-sections leading to the selected transducer and the deselected L-sections within the selected branch and the first layer are visible to the signal line.

Note that added layers increase both the cross talk isolation and the effective $R_{DS}(on)$. Two layers provide sufficient isolation to reduce the contamination of the velocity signal well below 10%. Each layer increments $R_{DS}(on)$ by 0.6 Ω, approximately 10% of the T/R impedances. This suggests an upper limit of 3 or 4 layers. Either of these restrictions may constrain the load optimization.

For a general tree with l layers and n_i L-sections in each group of the i^{th} level the following relationships hold. The tree multiplexes $\Pi_{i=1}^{i=l} n_i$ transducers. The number of selected L-sections seen by the signal line is equal to l, the number of layers. The number of deselected L-sections contributing to the signal load is $\Sigma_{i=1}^{i=l} n_i - l$. For example, the trees in Figure 4 each multiplex 24 transducers through 2 layers with $n_1 = 4$ and $n_2 = 6$. The signal line is shunted by 2 selected and 8 deselected L-sections.

It can be shown that, for a given set, $\{n_i\}$, structuring the layers to arrange the elements of the set in ascending order will minimize the number of FETs required with no change to the net impedance. Additionally, reducing the range spanned by the elements in the set, $\{n_i\}$, increases the number of FETs, but has the more important consequence of maximizing the shunt impedance for a given number of layers. It is desirable to maximize the shunt impedance and then minimize the number of FETs necessary to achieve that impedance. These criteria determine the optimum set, $\{n_i\}$, for a given number of layers and transducers. If a single T/R board is used with each half of a T/R circuit multiplexed to 24 transducers, the optimum structures for trees of 1, 2, 3, and 4 layers are $\{24\}$, $\{4,6\}$, $\{2,3,4\}$, and $\{2,2,2,3\}$. The second of these is shown in Figure 4.

Now observe that each added layer increases the load by one selected L-section and decreases it by some number of deselected sections. Assuming that the optimal set, $\{n_i\}$, is used at each level, the optimal configuration for a given number of T/R circuits, that is, for a given level of measurement flexibility, follows as a simple consequence of the different shunt values for the two L-section states. For a selected L-section the nominal equivalent shunt capacitance is 505 pF with a maximum of 716 pF. The values for a deselected L-section are 65 pF and 116 pF. The selected to deselected capacitance ratios are 8:1 and 6:1. Therefore, when adding a layer removes more than 6 to 8 deselected L-sections from view the net shunt impedance is increased. When fewer are eliminated the net shunt impedance decreases. With the number of T/R boards constrained by the desired level of measurement flexibility, the structure of the tree can be optimized for maximum shunt impedance.

For a single T/R board each half of a T/R circuit would be multiplexed to 24 transducers placed at odd or even vertical levels. This is a very reasonable level of measurement flexibility. The change from one to two layers hides 15 deselected L-sections. The change from two to three layers removes only 2 more from view. The two layer configuration shown in Figure 4 is demonstratably the optimum layered multiplexer when a single T/R board is used. Additionally, the cross talk isolation and effective $R_{DS}(on)$ of a two layer multiplexer are acceptable and therefore do not constrain the minimization of signal loading. Two layers is also optimal when either two or three boards are used. Additional boards increase the signal shunt impedance at the cost of measurement flexibility. Turbulent length scales in the wave boundary layer suggest that 2 to 3 T/R boards, 8 to 12 T/R circuits, is the practical limit if the transducer connection pattern along the tine is periodic.

The question now arises, does the optimal layered multiplexer, which meets all of the other stated requirements for the interface, provide a sufficiently high shunt impedance to prevent excessive signal loading? There are a number of other loads on the signal line that should be considered. The transducers are capacitive loads averaging $80\,pF$ ($\sim 1\,K\Omega$ at $1.75\,MHz$). The transmission line is a shunt load of $\sim 50\,pF$ ($\sim 2\,K\Omega$). The transmitter source impedance is $5\,\Omega$ to $10\,\Omega$ and the receiver load impedance is $12\,\Omega$ to $16\,\Omega$. The shunt load presented by the two layer, single board tree shown in Figure 4 is $1500\,pF$ to $2400\,pF$ ($59\,\Omega$ to $38\,\Omega$). The range for a two layer, two board tree, $1300\,pF$ to $2000\,pF$ ($68\,\Omega$ to $45\,\Omega$), is similar.

Due to transmitter diodes and receiver blanking the transmitter is loaded, through the source resistance, by both multiplexer tree-transmission line shunt-transducer circuits, but not by the receiver [6]. These elements form a voltage divider with a response dominated by the impedance of the multiplexers. The divider attenuates the transmitter voltage by 15 % to 35 %. The transmitter voltage is adjustable and can be set for a $\pm 5\,V$ signal at the transducer, a voltage driven device. The maximum amplitude, $8\,V$, is determined by the $\pm 12\,V$ gate control voltage and the $\pm 20\,V$ gate-source breakdown voltage. The $5\,V$ level is preferable to reduce signal dependent variations in $R_{DS}(on)$. Signal loading during transmission will be heavy, but not absolutely prohibitive.

When receiving an acoustic signal each transducer is loaded by its own capacitance and transmission line, a single multiplexer tree, and the receiver impedance. For acoustic reception the transducer is best modeled as a current source driving the load. The receiver is a cascode circuit which converts the current through the receiver impedance, the small equivalent impedance seen looking into the cascode emitter input, into an amplified voltage signal at the cascode output. The response of the current divider formed by the various loads, like the voltage divider of the transmitting circuit, is dominated by the impedance of the multiplexers. 70 % to 80 % of the transducer current is delivered to the receiver.

The equivalent circuit fragment in BASS, because of the long coaxial transmission line and larger diameter transducer used, presents essentially the same capacitive shunt load to the transducer current source. 75 % of that current is delivered to the receiver. This suggests that signal loading during recpetion will also be acceptable. However, the transducers to be used in the BASS Rake have a much smaller diameter than those used in BASS and their drive capabilities are currently unknown. At a minimum $\pm 0.5\,mA$ should be delivered to the receiver load for good signal quality [6]. Should the transducer prove inadequate to this task, an additional modification to the basic L-section can be made that will increase the overall shunt impedance of the multiplexer.

The primary path of the shunt is through the gate terminals of the FETs to the $\pm 12\,V$ power supplies. Gate resistors will therefore increase the shunt impedance. They will also increase the switching time of the tree. The capacitance looking into the gate depends on the state of the FET switch. To maintain an RC time constant below $2\,\mu s$ independent of the state, gate resistors up to $3\,K\Omega$ in size may be used. A time constant up to $10\,\mu s$ using a $15\,K\Omega$ input resistor, would be acceptable. The effect of the added impedance on the tree is to flatten the optimum impedance peak and shift it slighly towards deeper layering. The effect increases with resistance, but the rate of change is steepest for low resistance. Given the constraint on $R_{DS}(on)$ and the smoothness of the optimizing peak, a two layer tree remains the best choice. The nominal shunt impedances of the tree shown in Figure 4 for $1\,K\Omega$, $3\,K\Omega$, and $15\,K\Omega$ gate resistors are $154\,\Omega$, $230\,\Omega$, and $258\,\Omega$. The minimum values are $108\,\Omega$, $134\,\Omega$, and $140\,\Omega$. With $3\,K\Omega$ resistors and a $2\,\mu s$ time constant, 90 % of the transducer current is delivered to the receiver load.

V. SUMMARY

The physical scales of the wave bottom boundary layer impose a number of constraints on the design of an instrument intended to image the dynamic structure of the flow. Meeting these sensor constraints and those of the BASS T/R circuit requires a multiplexer interface providing low through resistance, rapid switching, flexible cross connection, and good isolation. The design of the layered multiplexer described here has been shown to meet these requirements. A two layer multiplexer is currently under construction for laboratory evaluation.

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