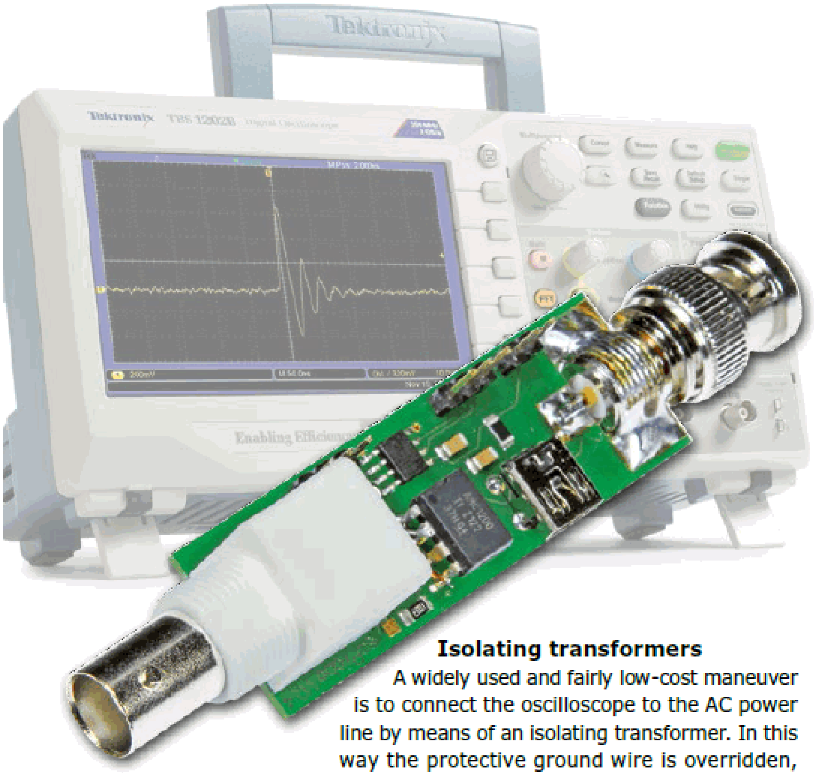
Isolated Oscilloscope Probe

Petite and practical



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However much you might wish for an oscilloscope with electrically isolated inputs, it's hard to justify the cost for personal projects. Even differential probes, which (within certain limits) enable voltages to be measured without reference to ground, often cost the private user more than a complete scope does. So what can you do when either safety considerations or the nature of the task in hand require the use of isolated connections to your oscilloscope?

Isolating transformers

A widely used and fairly low-cost maneuver is to connect the oscilloscope to the AC power line by means of an isolating transformer. In this way the protective ground wire is overridden, eliminating any danger of live circuit elements becoming grounded when the probe is attached. Any risk of a short circuit and possible destruction of the circuitry is thus averted. Conversely a clear hazard remains, in that the probe leads might become energized at high potential (AC line voltage for instance), putting parts of the oscilloscope equally at risk. In particular the BNC connectors of channels not in use at the time could be rendered live (and these are not protected against accidental touch).

When multiple probes are connected, these too could become live, so ideally they need to be placed where there is no risk of accidental contact with them. In the worst case these probes might be connected to other part of the circuitry under

Features

- Electrical separation of 1 analog signal and 2 digital signals
- Max. input voltage ±250 mV (or ±2.5 V/±25 V, determined by jumper)
- Amplification factor between input and output: 8 x (without voltage divider on input)
- Signal bandwidth, analog input: 60 kHz
- Signal bandwidth, digital inputs: 1 Mbps
- Power supply via separate AC adapter or Mini USB connector
- Power requirements: 5 V; 110 mA

examination and cause the isolating transformer to become short-circuited.
For these reasons the isolating transformer method is reliable only for making electrically isolated measurements on one single channel, at low voltages. When two channels are involved, with most scopes you can, in principle, make differential measurements (e.g. channel 1 minus channel 2), but the input wiring of the channels imposes limitations on matters such as common mode rejection range. Accordingly the isolating transformer method should not be first choice for an experimenter taking measurements on high voltages.

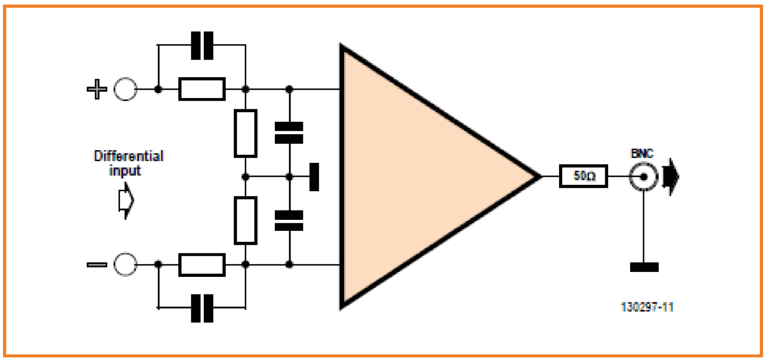

Figure 1.
Block diagram of a differential probe. The input circuitry consists of the voltage divider (high impedance series resistor) and comparatively low resistance resistor in parallel at each input.

Differential probes

Moving on, differential probes are the next more expensive method for making measurements without reference to ground. The illustration in **Figure 1** shows the schematic circuit of a differential probe. The input wiring consists of a voltage divider (high-value series resistance) on each of the Positive and Negative inputs, together with a comparatively low-value resistor in parallel with the input of the opamp. The high-impedance connection to the inputs ensures that even at high offset voltages only a small current flows through the series resistors. Since the offset is generally the same for both inputs (e.g. high-side shunt measurements), the differential voltage does not upset the opamp.
The limiting factor here is the common-mode suppression of the opamp, since at larger offset voltages the common mode rejection range is exceeded sooner or later. In every case the limit is the supply voltage of the opamp. In practice these are often provided with a voltage of ±4.5 V supplied from a 9-V 6F22 (PP3-size) battery. Accordingly, with a voltage divider of 10:1, the maximum voltage you should connect to the inputs of a probe is ±45 V. If you raise the division factor to 100:1, theoretically you could go up to ±450 V and in this way use a shunt to take measurements across a 230 VAC or 115 VAC circuit. That said, you must operate only in voltage ranges for which the components used in the input circuitry are rated for adequate dielectric strength. In other words, not every differential probe is suitable. In addition, the greater the division factor for the input voltage, the more you correspondingly reduce the signal being measured. This (if you are using shunts) is already tiny, since shunts are configured with as low resistance as possible to prevent power dissipation. For example, a useful signal of ±250 mV with an offset of +40 V produces, for a division ratio of 10:1, a signal of ±25 mV with 4 V offset. If we set the oscilloscope for 1 V/Div, to center the 4 V at the middle of the display, the wanted signal amounts to just 1/40 Div. Even if you set the scope to show 0.1 V/Div, the signal we are trying to display amounts to just 1/4 Div, which corresponds to a resolution of only 3 bits (assuming 8-bit vertical resolution). On top of this, to see the entire signal on the display you would need to displace the vertical position of the oscilloscope by -40 V, which is barely feasible even on expensive scopes.

Hopeless task?

Given that the restricted common mode rejection range and the undesired reduction of the wanted signal produce contrary demands on the input circuit design, there is always a compromise when using differential probes. However, the use of electrically isolated probes offers an elegant solution here. This approach allows unrestricted connection to high voltages, without any high offset voltage arising on the inputs of the internal opamps. Moreover, an electrically isolated probe has advantages even when high offset voltages are not involved, such as when ground loops must be avoided.

Selecting suitable components

The Internet is brimming with homebrew circuits for isolated probes and discussions about the hookups employed. Nevertheless it soon becomes apparent that most of these solutions rely on using differential probes that do not provide genuine electrical isolation. To keep our circuit simple, we too settled against a true differential probe and opted for a circuit using a simple isolation

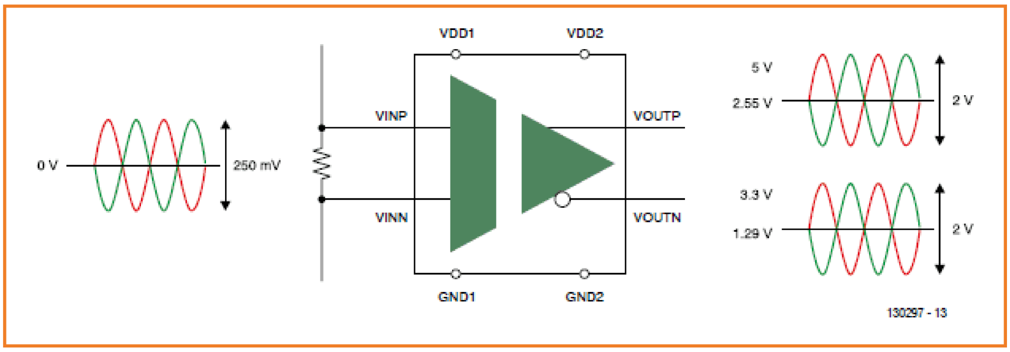

Figure 2.
The AMC1200 is a "fully differential isolation amplifier" capable of handling input voltages up to ±250 mV.

amplifier for a single probe, as this seemed to represent the commonest need in semi-professional circles.

For its functioning an electrically isolated opamp requires two separate supply voltages that are each isolated electrically from one another. The supply for the output side can share the same ground potential as the oscilloscope, whereas the input side must not share any ground reference with the scope. The simplest solution is to use a pair of 9 V 'block' batteries to produce the ±4.5 V supply voltage (one for the input side of the opamp and one for the output). The physical size of two 9 V batteries (each H: 48.5, L: 26.5, W: 17.5 mm) plus the constant need to have two fresh batteries on hand are admittedly distinct disadvantages.

An electrically isolated DC/DC converter is another possibility for powering the input of the opamp, making one additional single supply voltage necessary for the output side. The typically low current demand of an opamp permits the use of a small DC/DC converter, requiring few external components. The secondary voltage must naturally go well with the electrically isolated opamp employed.

The search for an appropriate opamp didn't take long and we rapidly opted for the well-known ISO series from Burr Brown (now Texas Instruments), specifically the ISO124 [1]. Its isolation rating is 1500 V with an amplification factor of 1 (unity gain) and a supply range from ±4.5 V up to ±18 V. The signal bandwidth for the ISO124 is typically 50 kHz. This is of course rather small, even when considered against the 10 to 100 MHz bandwidth of a low-cost oscilloscope. Nevertheless the analog voltages encountered in the semi-professional range would typically not exceed this bandwidth.

However, to keep costs down we opted for the AMC1200 [2] from the same manufacturer. Once again we're talking about an electrically isolated opamp (**Figure 2**), which is configured primarily for taking high-side shunt measurements. It operates from a simple supply voltage of 5 V on each side and has an input voltage range of ±250 mV plus a fixed gain factor of 8. So with ±250 mV at the input we have ±2 V on the output. The signal bandwidth is 60 kHz, which in our opinion is satisfactory for this application. Current consumption is agreeably low at typically 5 mA, enabling a small DC/DC converter from the iCoupler range made by Analog Devices to be used along with a straightforward 5 V supply. What we have here is an electrically isolated coupler predominantly for digital signals, e.g. such as SPI or I2C interfaces. Some of the components in this range, however, have in addition to the couplers for the digital signals a low-power 5 V/5 V DC/DC converter on board, providing what AD calls "isoPower". Primarily this is for serving the coupler's own supply needs but it has a small power reserve that is adequate for our AMC1200. The ADuM5242 [3] we selected comes in SOIC-8 package format and is therefore easy to solder by hand. In addition to the DC/DC converter there are also two digital couplers on

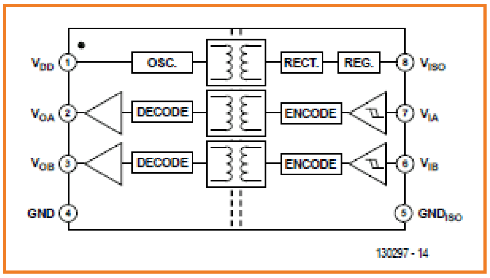

Figure 3.
Block diagram of the AduM5242, a two-channel isolator with integrated DC/DC converter.

board (**Figure 3**), enabling our circuit not only to measure the electrically isolated analog voltage but also to handle two digital signals, again in electrical isolation.
Two pin-compatible variants exist also, the ADuM5240 and 5241, offering two independent isolation channels in a variety of channel configurations. Configured appropriately, these can be used for electrically isolated control of digital signals in the measurement circuitry. One disadvantage of the iCoupler chip and its integrated DC/DC converter is the rather restrained efficiency factor of the converter, which is less than 20 %.

We now have an all-5 V solution; 5 V supplies are widely available and should be easy to find virtually everywhere. If nothing else, many modern oscilloscopes possess a connector for USB memory sticks, through which our circuit could also be powered.

For sake of completeness it should also be mentioned that significantly more powerful isolation amplifiers are also available, such as the AD216 from Analog Devices [4]. This offers double the bandwidth (120 kHz) and even contains an integrated DC/DC converter for the electrically isolated supply for the input side. It does, however, require a bipolar power supply of ±15 V and costs six times the price of the combination of ADuM5242 and AMC1200.

The circuit

The circuit in **Figure 4** is comparatively simple and consists essentially of the components already described. The ADuM5242 (U1) generates the electrically isolated voltages 5 V (VCCiso) and 0 V (GNDiso) for the input side. The two electrically isolated digital channels are taken to a simple three-pin connector strip CON5. The supply for the AMC1200 (U2) is fed via a small choke, which smoothes the output voltage of the ADuM5242 a little more.
The negative opamp input is connected to VCCiso/2 via a 1:1 voltage divider (R5/R6), so that the voltage on the positive input at this point can swing ±250 mV at full range. To extend the measurement range to ±2.5 V or alternatively ±25 V we employ the voltage dividers R2/R3 and R2/R4, activated using jumpers J1 and J2 respectively. The jumper settings are as follows:

1:1	J1: closed	J2: open
10:1	J1: open	J2: 1-2
100:1	J1: open	J2: 2-3

As the voltage dividers have very high resistance (in order to load or degrade the signal source as little as possible) as opposed to the AMC1200, which with 28 kΩ has relatively low differential input resistance, we employ the simple opamp U3 in the signal path as an impedance converter. The oscilloscope probe is connected via CON6

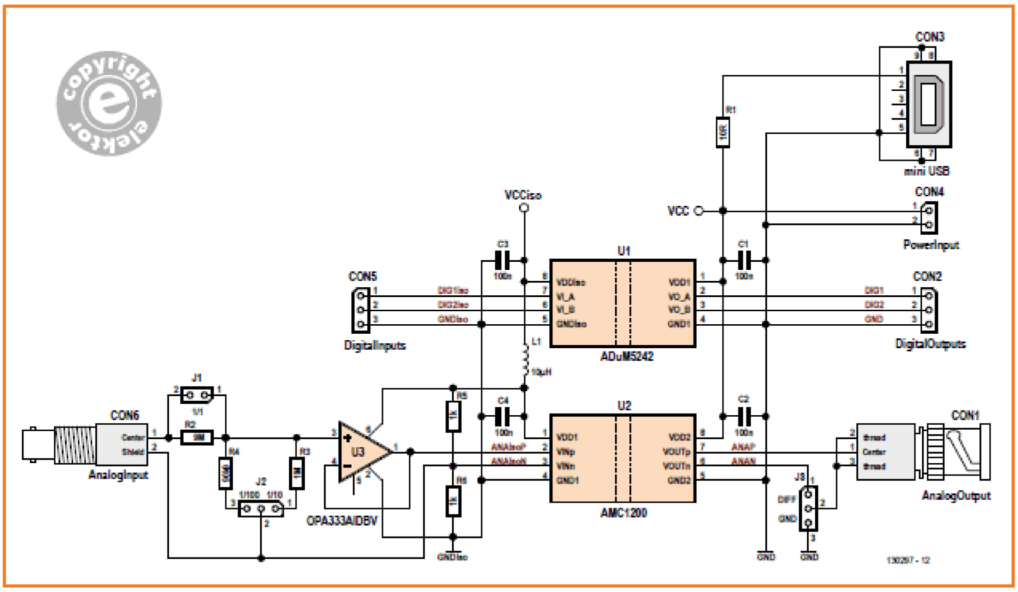

Figure 4.
The circuit is relatively simple and consists essentially of an ADuM5242 (U1) and an AMC1200.

Component List

Resistors
(SMD 1206)
R1 = 10Ω
R2 = 9MΩ
R3 = 1MΩ
R4 = 100 kΩ
R5,R6 = 1kΩ

Capacitors
C1–C4 = 100nF (SMD 1206)

Inductors
L1 = 10µH (SMD 1206)

Semiconductors
U1 = AduM5242 (SOIC-8)
U2 = AMC1200 (SOP-8)
U3 = OPA333AIDBV (SOT-23)

Miscellaneous
CON1 = BNC plug, panel mount
CON2,CON5 = 3-pin pinheader, 0.1″ pitch
CON3 = mini-USB receptacle
CON4 = 2-pin pinheader, 0.1″ pitch
CON6 = BNC socket, panel mount
PCB # 130297-1 [5]

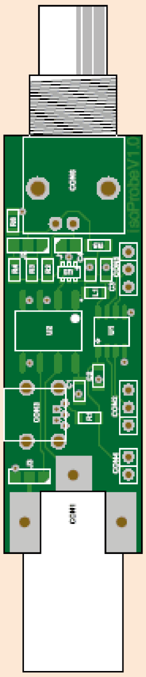

Figure 5.
The circuitry goes together rapidly on this small printed circuit board.

to the input of the voltage divider and the negative input of the AMC1200. At this point the shield terminal of the probe certainly is not at GNDiso potential but this is not problematic, for one thing because the circuit is “suspended in mid-air” and entirely potential-free thanks to the electrical isolation. The other reason is to enable the input voltage to then swing versus the ground connection according to the setting of the voltage divider by respectively ±250 mV, ±2.5 V or ±25 V.
Problems arise only when the digital channels are in use and for this GNDiso (pin 3 of CON5) needs to be linked to the ground of the measurement circuit. Doing this also takes the negative input of the AMC1200 down to ground, with the measurement range becoming then only a unipolar +250 mV (+2.5 V/+25 V), relative to the shield terminal of the probe. Nevertheless this is no more than only a minor limitation, since the circuit is designed primarily for making analog measurements and the two digital channels are purely a bonus gift from the ADuM5242.
Incidentally, instead of using the voltage divider specified, our circuit can also operate with a 10:1 or 100:1 probe to increase the measurement range (J1: closed, J2: open).

The connections to the power supply and probe input from the oscilloscope CON1 are located on the output side of the circuit. The best possible performance is achieved when the circuit is powered, via CON4, from an electrically isolated lab power supply unit. The supply voltage is then fully isolated from the oscilloscope and the scope input can be hooked up to the differential outputs of the AMC1200 (jumper J3: 1-2). The signal then swings (at full range) by ±2 V either side of oscilloscope ground. The gain of 8 in the AMC1200 produces a differential aggregate transfer factor, from input to output, of 1:8, 10:8 and 100:8, which correspondingly needs to be taken into consideration when taking readings of the oscilloscope voltage. If your scope provides fine adjustment of the vertical graduation, you can alter this to, say, 125 mV/Div and then take readings with the circuit set to 1:8, as if you had set the scope to 1 V/Div.

The circuit also includes a 5-pole Mini USB-B connector for obtaining power from, say, the USB memory stick connector on an oscilloscope. In this situation the ground connection of the probe input CON1 will be at GND potential at the oscilloscope end and jumper J3 must then be set at position 2-3. If this was not done, negative AMC1200 output would be short-circuited to GND. In this configuration the output signal on the oscilloscope has a fixed offset of around VCC/2 (2.55 V, see AMC1200 data sheet) and the centre point amounts to only half of this, since we are using only one out of the two differential output signals currently. In this situation the transfer factors mentioned above are halved correspondingly. Taking the power supply from a USB connection is really an emergency expedient, as the purity of the voltage on a USB bus is not adequate for supplying analog circuitry and will be affected every now and again by interference arising from the inner digital regions of the scope.

Construction

The circuit uses only a few components and since these are predominantly large SMD devices, the PCB in **Figure 5** can be assembled rapidly. The PCB layout can be downloaded free from the project page [5].
The ADuM5242 comes in a SOIC-8 package and the AMC1200 in an even larger SOP-8 package, corresponding in essence to a DIP-8 package

equipped with angled pins for SMD mounting. All resistors and capacitors have the 1206 form factor, enabling them to be soldered without difficulty. The impedance converter U3 differs in having a small SOT-23 package and for this reason should be soldered into place with care as the first component to be fitted, followed by the ADuM5242 and the AMC1200. After this come the SMD resistors and capacitors and the wound components. Since BNC plugs for 90° mounting on printed circuit boards are extremely uncommon, we have provided the PCB with a suitable cut-out to enable a normal panel-mounting BNC connector to be fitted. To solder it in place you will need a soldering iron with adequate wattage to bring the metal thread of the connector rapidly to the melting point of the solder, without degrading the plastic insulation inside. The unit is remarkably compact and can be inserted conveniently between the oscilloscope and probe.

Commissioning

As a result of the low efficiency factor of the ADuM's DC/DC converter (less than 20 %), the current consumption of the complete circuit is around 110 mA. This figure should be checked after constructing the circuit and connecting it to a 5 V power supply. If you have one, it's advantageous to use a laboratory power supply with presettable current limiting. From preference, commissioning should not be carried out taking the supply from a USB connector. If the current drawn is significantly greater than the value quoted, checks should be made for possible soldering errors, short circuits or components inserted back to front. After this you should measure the supply voltage VCCiso on the secondary side, which is typically 5.2 V. If both of these values are correct, the circuit can be connected between oscilloscope and probe; you can then check out its correct functioning with a signal source and oscilloscope.

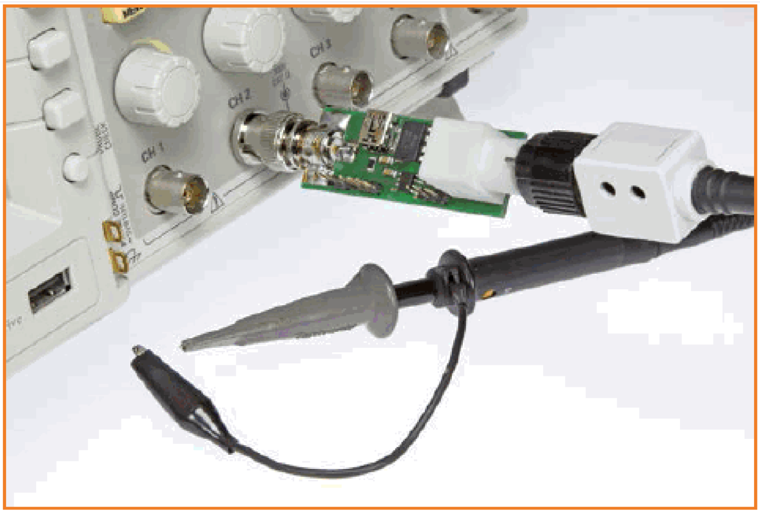

Figure 6.
The circuit put into practical use. The PCB of the prototype seen in this photo differs from the board shown in Figure 5.

Verdict

Using modern, low-cost components it's easy to construct a simple isolation amplifier for oscilloscope probes. The restricted analog bandwidth does admittedly restrict the potential applications, meaning that it's not feasible to measure, for example, the signal quality of differential high-speed signals (such as LVDS, USB or Ethernet). On the other hand, the true electrical isolation provided can occasionally be advantageous for connecting expensive differential probes, if the signal/offset relationship is of importance or when avoiding ground loops is a priority. The modest cost means you can also make several units of this circuit and equip every channel of your scope with electrical isolation. This isolation is provided not merely for the device under test, as could also be achieved with an isolating transformer; doing it this way, every channel is isolated from each other. Consequently you can take potential-free measurements at different points in a circuit with just one single oscilloscope.

(130297)

Web Links

[1] www.ti.com/product/iso124

[2] www.ti.com/product/amc1200

[3] www.analog.com/en/interface-isolation/digital-isolators/adum5242/products/product.html

[4] www.analog.com/en/specialty-amplifiers/isolation-amplifiers/ad215/products/product.html

[5] www.elektor-magazine.com/130297