

High Speed Digital Isolators Using Microscale On-Chip Transformers

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Introduction

In many industrial applications, such as process control systems or data acquisition and control systems, digital signals must be transmitted from various sensors to a central controller for processing and analysis. The controller then needs to transmit commands as a result of the analysis performed, coupled with user inputs to various actuators, to achieve certain operations. To maintain safety voltage at the user interface and to prevent transients from being transmitted from the sources, galvanic isolation is required. There are three commonly known classes of isolation devices: optocouplers, capacitively coupled isolators, and transformer based isolators.

Optocouplers rely on light emitting diodes to convert the electrical signals to light signals and on photo detectors to convert the light signals back to electrical signals. The intrinsic low conversion efficiencies for electrical light conversion and slow response photo detectors lead to optocoupler limitations in terms of lifetime, speed, and power assumption. The capacitively coupled isolators have limitations in their size and ability to reject common-mode voltage transients, while the traditional transformer assembly based isolators are bulky and expensive. All these isolators are restricted, moreover, because of integrated circuit integration limitations and the fact that they often need hybrid packaging.

Recently *iCoupler*®, a new isolation technology based on chip scale transformers, was developed by Analog Devices. The first product, the ADuM1100 single-channel digital isolator, is in volume production. *iCoupler* technology leverages thick-film processing techniques to build microscale on-chip transformers and achieves thousands of volts of isolation on a chip. *iCoupler* isolated transformers can be monolithically integrated with standard silicon ICs and can be fabricated in single- or multichannel configurations. The bidirectional nature of inductive coupling further facilitates bidirectional signal transfer. The combination of high bandwidth for these on-chip transformers and fine scale CMOS circuitry leads to isolators of unmatched performance characteristics in power, speed, timing accuracy, and ease of use.

ADuM1100 Architecture: A Single-Channel Digital Isolator

The ADuM1100 is a single-channel 100 Mbps digital isolator. It has two ICs packaged in an 8-lead SOIC package. A cross-section view of the ADuM1100 is shown in Figure 1. There are two lead frame paddles inside the package, with gap between them of about 0.4 mm. The molding compound has breakdown strength over 25 kV/mm, so the 0.4 mm gap filled with molding compound provides greater than 10 kV insulation between the substrates of two IC chips.

The driver chip sitting on the left paddle takes the input digital signal, encodes it, and drives the encoded differential signal through bond wires to the top coils of the transformers built on top of the receiver chip sitting on the right paddle. The driver die is a standard CMOS chip, and the receiver die, shown in Figure 2, is a CMOS chip with the additional structures of two polyimide layers and transformer primary coil fabricated on top of the passivation. The polyimide between the top and bottom coils is about 20 nm thick. Some primary characteristics of this polyimide are shown in Table 1. The breakdown strength of the cured polyimide film is greater than 300 V/ μm , so 20 μm of polyimide provides greater than 6 kV of insulation between a given transformer's coils. This provides a comfortable margin over the production test voltage of 3 kVRMS. Because of the structural quality of these wafer processed polyimide films, no partial discharge over 5 pC can be detected, even at 3 kVRMS. The top coil is gold plated, with a 4 μm thick layer, and the coil track width and spacing between the turns are all 4 μm . The polyimide layers have good mechanical elongation and tensile strength, which also helps the adhesion between the polyimide layers or between polyimide layer and deposited metal layer. The minimum interaction between the gold film and the polyimide film, coupled with high temperature stability of the polyimide film, results in a system that provides reliable insulation when subjected to various types of environmental stresses.

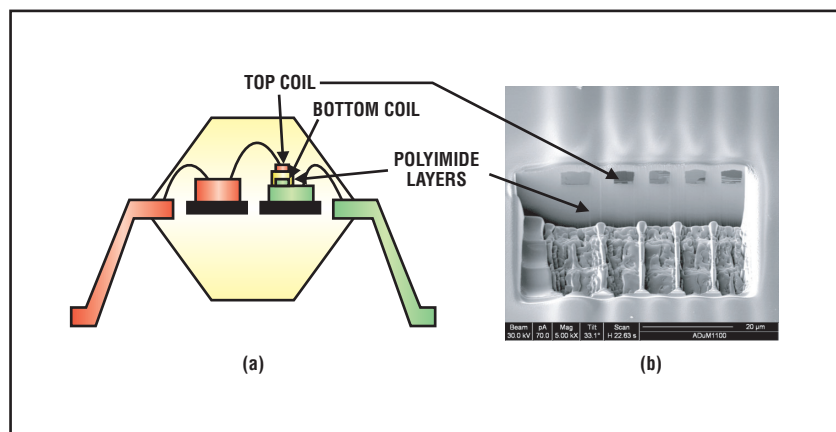


Figure 1a. Cross-sectional view of ADuM1100 in an 8-lead SOIC package; Figure 1b. Cross-sectional view of top coil and polyimide layers

Characteristics	
Weight Loss = 5% at T = (°C)	≥500
CTE (ppm)	40~50
Tensile Strength (Mpa)	>150
Mechanical Elongation (%)	>50
Young's Modulus (Gpa)	3.3
Electrical Dielectric Constant	3.3
Moisture Uptake (%)	0.8
Breakdown Voltage	>300 V/ μm

Table 1. Polyimide properties

In addition to the fact that thousands of volts of isolation can be achieved on-chip, the ADuM110 also makes it possible to transmit very high bandwidth signals very efficiently, accurately, and reliably. Figure 3 is a simplified schematic of the ADuM1100. To guarantee input stability, the front glitch filter filters out pulses narrower than a pulse width of approximately 2 ns. Upon the receipt of a signal edge, a 1 ns pulse is sent to either Coil 1 or Coil 2. (For a leading edge signal it is sent to Coil 1, and for a falling edge signal to Coil 2.) Once the short pulses are transmitted to the secondary coils (the bottom coils in this case), they are amplified and the input signal is reconstructed through an SR flip-flop to appear as an isolated output. The wide bandwidth of these microscale transformers and high speed CMOS make the transmission of these short nanosecond pulses possible. Since only signal edges are being used, this transmission scheme is very power efficient. With a very energetic pulse having a current ramping to 100 mA within 1 ns, the average current for a 1 Mbps input signal is only 50 μ A. Some additional power is dissipated by the switching of the surrounded CMOS gates.

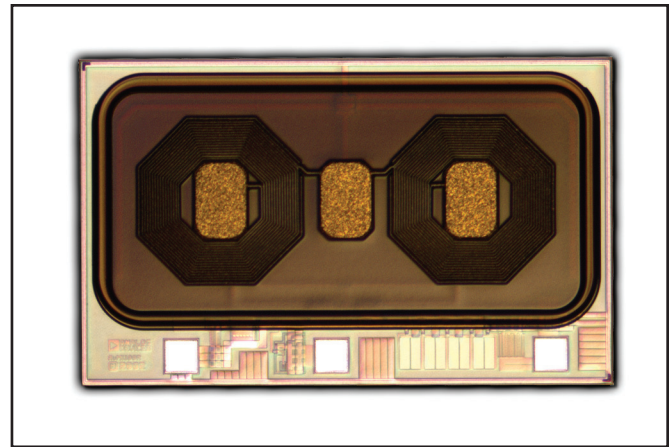


Figure 2. ADuM1100 receiver chip

At 5 V, an additional 50 μ A/Mbps is needed if the total capacitance of the CMOS gates is 20 pF. The typical optocoupler, on the other hand, dissipates over 10 mA, even operating at 1 Mbps. This represents two orders of magnitude ($100\times$) improvement in power dissipation provided by iCoupler isolators.

If there is no input change for a certain period of time, approximately 1 μ s, the monostable generates a 1 ns pulse and sends it to Coil 1 or Coil 2, depending on the input logic level. The 1 ns refreshing pulse is sent to Coil 1 if input is high and is sent to Coil 2 if input is low. This helps maintain dc correctness for the isolator because normally pulses are transmitted only on reception of a signal edge. The receiver includes a watchdog circuit that will timeout at 2 μ s if it is not reset by an incoming pulse. If a timeout happens, the receiver output will return to a default safe level (logic high in the ADuM1100). The combination of refresh and watchdog functions provides the additional advantage of detecting the failure of any field device on the system side. With other isolators, this would ordinarily require the use of an extra isolated data channel.

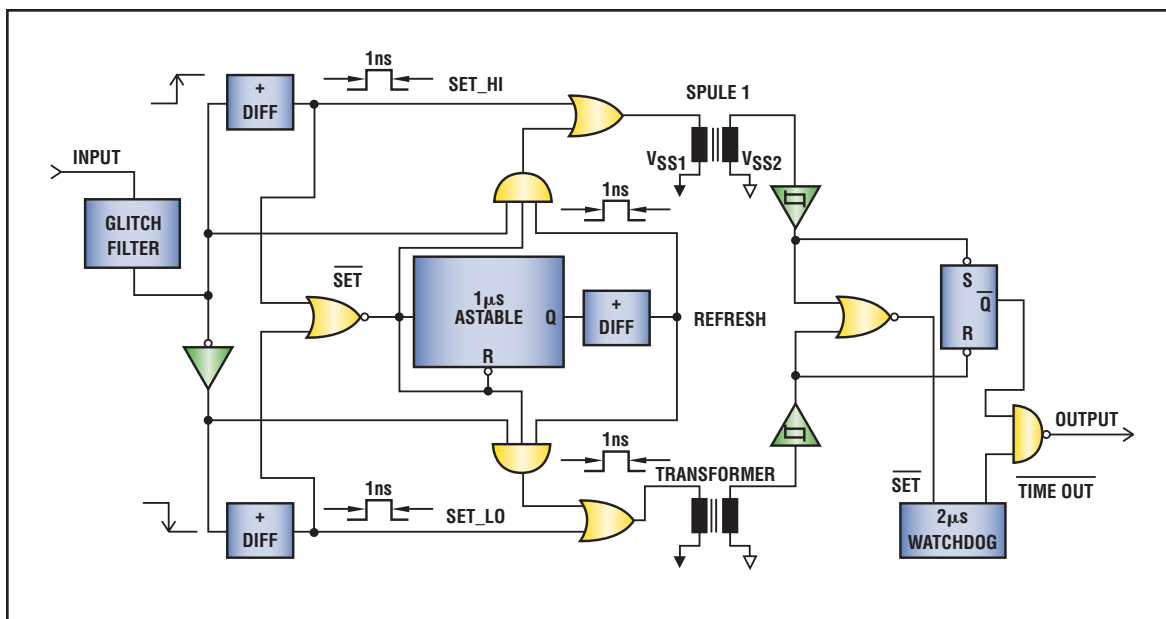


Figure 3. ADuM1100 circuit diagram

The bandwidth of the isolator is dependent on the input filter bandwidth within. For example, 500 Mbps can be achieved with a 2 ns input filter. For the ADuM1100, we chose a signal bandwidth of 100 MBd, still $2 \times$ faster than the fastest optocouplers. Very tight edge symmetry between input and output logic signals is also preserved due to the instantaneous nature of the inductive coupling between these microscale on-chip coils. The ADuM1100 has edge symmetry of better than 2 ns for 5 V operation. As the bandwidth of isolation systems continues to expand, the iCoupler technology will be capable of meeting the challenge while optocoupler technology is likely to struggle. Table 2 summarizes the existing performance characteristics of the iCoupler technology as provided by the ADuM1100 digital isolator.

Parameter	ADuM1100AR/BR
Data Rate (Mbps, min)	25/100
Supply Current at 10 Mbps, max (mA.)	2.0
Propagation Delay, max (ns)	18
Pulse Width Distortion, max (ns)	2
Propagation Delay Skew, max (ns)	6
Common-Mode Transient Immunity, min (kV/ μ s)	25
Isolation Rating (V)	2500
Temperature Range ($^{\circ}$ C)	-40 to +125

Table 2. ADuM1100 characteristics

In addition to the improvements in efficiency and bandwidth iCoupler technology provides, it also offers a more robust and reliable isolation solution than competitive offerings. Because high voltage transients are present in many data acquisition and control systems, the ability of the isolator to prevent transients from affecting the logic controller is very important. High performance optocouplers have transient immunity of less than 10 kV/ μ s, while the ADuM1100 has a transient immunity better than 25 kV/ μ s. The induced error voltage at the receiver input induced by an input-output transient is given by:

$$V = CR \, dV/dt$$

where:

C is the capacitance between the input coil and the receiver coil

R is the resistance of the bottom coil

dV/dt is the magnitude of the transient

In the ADuM1100, the capacitance between the top (input) coil and the bottom (receiver) coil is only 0.2 pF, while the bottom coil has a resistance of 80 Ω . Thus the error signal induced on the bottom coil by a 25 kV/ μ s transient on the top coil is only 0.4 V, much less than the receiver detection threshold. The transient immunity of iCoupler isolators can be optimized through careful selection of the decoder detection threshold, the resistance of the receiving coil, and, of course, the capacitance between the top and bottom coils.

One recurring question about transformer based isolators involves their magnetic immunity capability. Since iCouplers use air core technology, no magnetic components are present and the problem of magnetic saturation for the core material does not exist. Therefore, iCouplers have essentially infinite dc field immunity. The limitation on the ADuM1100's ac magnetic field immunity is set by the condition in which the induced error voltage in the receiving coil (the bottom coil in this case) is made sufficiently large, either to falsely set or reset the decoder. The voltage induced across the bottom coil is given by:

$$V = (-d\beta/dt) \sum \pi r_n^2; n=1,2,\dots,N$$

where:

β = magnetic flux density (Gauss)

N = number of turns in receiving coil

r_n = radius of nth turn in receiving coil (cm)

Because of the very small geometry of the receiving coil in the ADuM1100, even a wire carrying 1000 A at 1 MHz and positioned only 1 cm away from the ADuM1100 would not induce an error voltage large enough to falsely trigger the decoder. Note that at combinations of strong magnetic field and high frequency, any loops formed by printed circuit board traces could induce error voltages sufficiently large to trigger the thresholds of succeeding circuitry. Typically the PC board design rather than the isolator itself is the limiting factor in the presence of such big magnetic transients.

In addition to magnetic immunity, the level of electromagnetic radiation emitted from the iCoupler device is a concern. Using far-field approximation:

$$P = 160\pi^2 I^2 \sum r_n^4; n=1,2,\dots,N$$

where:

P = total radiated power

I = coil loop current

Again, given the very small geometry of the coils, the total radiated power is still less than 50 pW, even if the part is operating at 0.5 GHz.

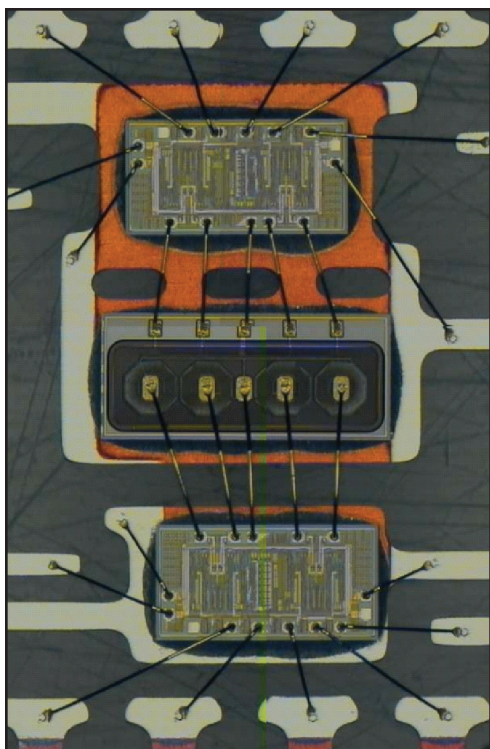


Figure 4. ADuM140x die photo

ADuM130x/ADuM140x: Multichannel Products

In addition to the many performance improvements discussed previously, *i*Coupler technology also offers tremendous advantages in terms of integration. The optical interference makes the realization of multichannel optocouplers very difficult. Transformers based on *i*Coupler technology can be easily integrated onto a single chip. Furthermore, one data channel can transmit signals in one direction, say from the top coil to the bottom coil, while the neighboring channel can transmit a signal in the other direction, from the bottom coil to the top coil. The bidirectional nature of inductive coupling makes this possible.

Analog Devices is currently sampling the ADuM130x/ADuM140x family of multichannel products, which consists of five 3-channel and 4-channel products covering all possible channel directionality configurations. Besides providing flexible channel configurations, they support both 3 V and 5 V operation at either side of the isolation barrier and support the use of these isolators as level translators. One side could be at 2.7 V, for example, while the other side could be at 5.5 V. The edge symmetry of 2 ns is preserved over all possible supply configurations at all temperatures from -40°C to 100°C . The ability to mix bidirectional channels of isolation in a single package enables users to reduce the size and cost of their systems.

For the ADuM1100, two transformers are used to transmit a single channel of data. One is dedicated to transmit pulses representing the signal's leading edge or updating input high, and the other is dedicated to transmit pulses representing the signal's falling edge or updating input low. For the ADuM130x/ADuM140x product family, a single transformer is used for each data channel. The ADuM140x shown in Figure 4 has four transformers in total. The leading edge and falling edge are encoded differently, and the encoded pulses are combined in the same transformer; as a result, the receiver has responsibility for decoding the pulses to see whether they are for leading edge or falling edge. The output signal is then constructed correspondingly.

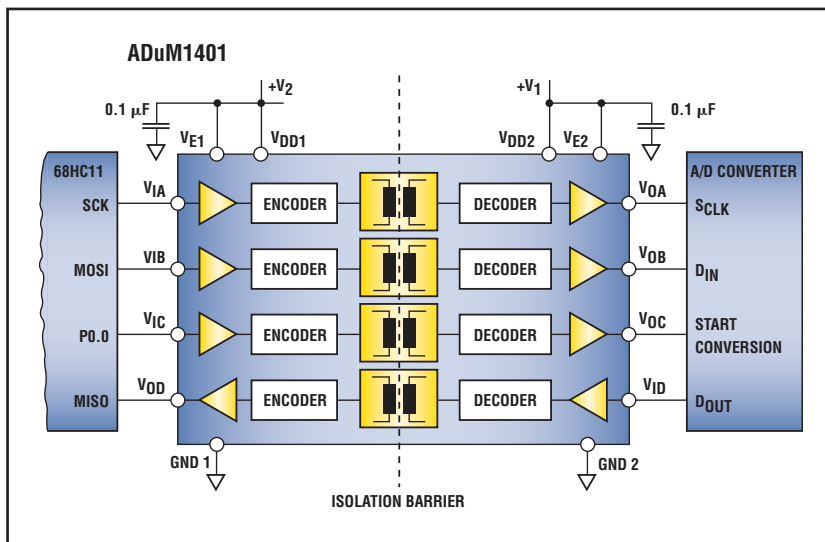


Figure 5. An SPI interface implemented using an ADuM1401 quad-channel isolator

Of course, there is a penalty for using a single transformer per data channel rather than using two transformers per data channel. The propagation delay is longer for the single transformer architecture because of the additional encode and decode time needed. The penalty for bandwidth is hardly a factor, even at input speed of 100 Mbps.

In contrast to the ADuM1100, the ADuM130x/ADuM140x uses a dedicated transformer chip, separate from the receiver integrated circuit. This partitioning exemplifies the ease of integration for *i*Coupler technology. Besides standalone multichannel isolators, the *i*Coupler technology can be embedded with other data acquisition and control ICs to make the use of isolation even more transparent. Consequently, in the future, system designers will be able to devote their time to improving system functionality, rather than worrying about isolation.

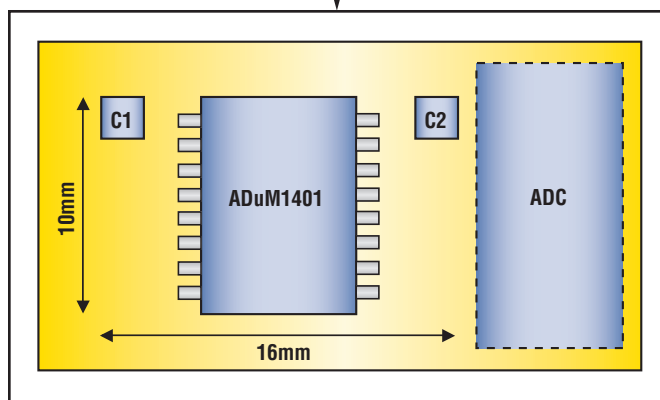


Figure 6. With the 4-channel ADuM1401, isolating an SPI interface requires only three components occupying 160 mm²

Summary

The tremendous advantages of *i*Coupler products over traditional optocouplers in terms of power consumption, signal bandwidth, robustness, and ease of integration make them ideal choices for future demanding isolation applications.

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