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A THREE CHANNEL TELEMETRY SYSTEM

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ABSTRACT

A three channel telemetry system intended for biomedical applications is described. The transmitter is implemented in a single chip using a 2 micron BiCMOS processes. The operation of the system and the test results from the latest chip are discussed. One channel is always dedicated to temperature measurement while the other two channels are generic. The generic channels carry information from transducers that are interfaced to the system through on-chip general purpose operational amplifiers. The generic channels have different bandwidths: one from dc to 250 Hz and the other from dc to 1300 Hz. Each generic channel modulates a current controlled oscillator to produce a frequency modulated signal. The two frequency modulated signals are summed and used to amplitude modulate the temperature signal which acts as a carrier. A near-field inductive link telemeters the combined signals over a short distance. The chip operates on a supply voltage anywhere from 2.5 to 3.6 Volts and draws less than 1 mA when transmitting a signal. The chip can be incorporated into ingestible, implantable and other configurations. The device can free the patient from tethered data collection systems and reduces the possibility of infection from subcutaneous leads. Data telemetry can increase patient comfort leading to a greater acceptance of monitoring.

INTRODUCTION

The three channel telemetry system was designed to fulfill a need in diagnostic medicine to measure physiological variables at the point of origin without prolonged invasive procedures. A generic system was developed to be interfaced with many types of sensors. The system was designed onto a 2.3 mm by 2.3 mm custom BiCMOS chip fabricated through the MOSIS service. The small size of the device permits both implantable and ingestible applications.

Circuit Operation

Figure 1 shows a block diagram of the three channel telemetry transmitter. The device transmits temperature and two user defined signals to the external receiver. The low frequency and high frequency channels are band-limited from 0 to 250 Hz and 0 to 1300 Hz respectively. The chip employs both frequency modulation and amplitude modulation to transmit the signals. The operation of a single channel will be detailed as the two channels differ only in the center frequency of the current controlled oscillator.

The descriptions that follow can be traced in the block diagram. The sensor output is amplified and conditioned by an operational amplifier. The on chip op-amps have low gain by traditional standards, but they are adequate for closed loop gains less than 50 provided allowance is made for the finite open-loop gain. The inputs transistors are MOSFET and so have inherently high input impedance and low bias current. The amplified sensor signal is converted to a current to drive the current controlled oscillator (ICO). The voltage to current converter has a differential input with the positive lead internally connected to the op-amp output, and the negative lead available for user connection to a reference point. The reference input is also a high impedance MOSFET input. The differential input voltage is driven across an on-chip 100 kΩ resistor to produce an output current. A fixed offset current (nominally 10 μA), derived from a band-gap generated voltage across an on-chip resistor is also added to the current output in order to set the ICO center frequency and allow both positive and negative deviations. This type of input circuitry provides significant flexibility; however, some types of sensors may require more sophisticated front end circuitry.

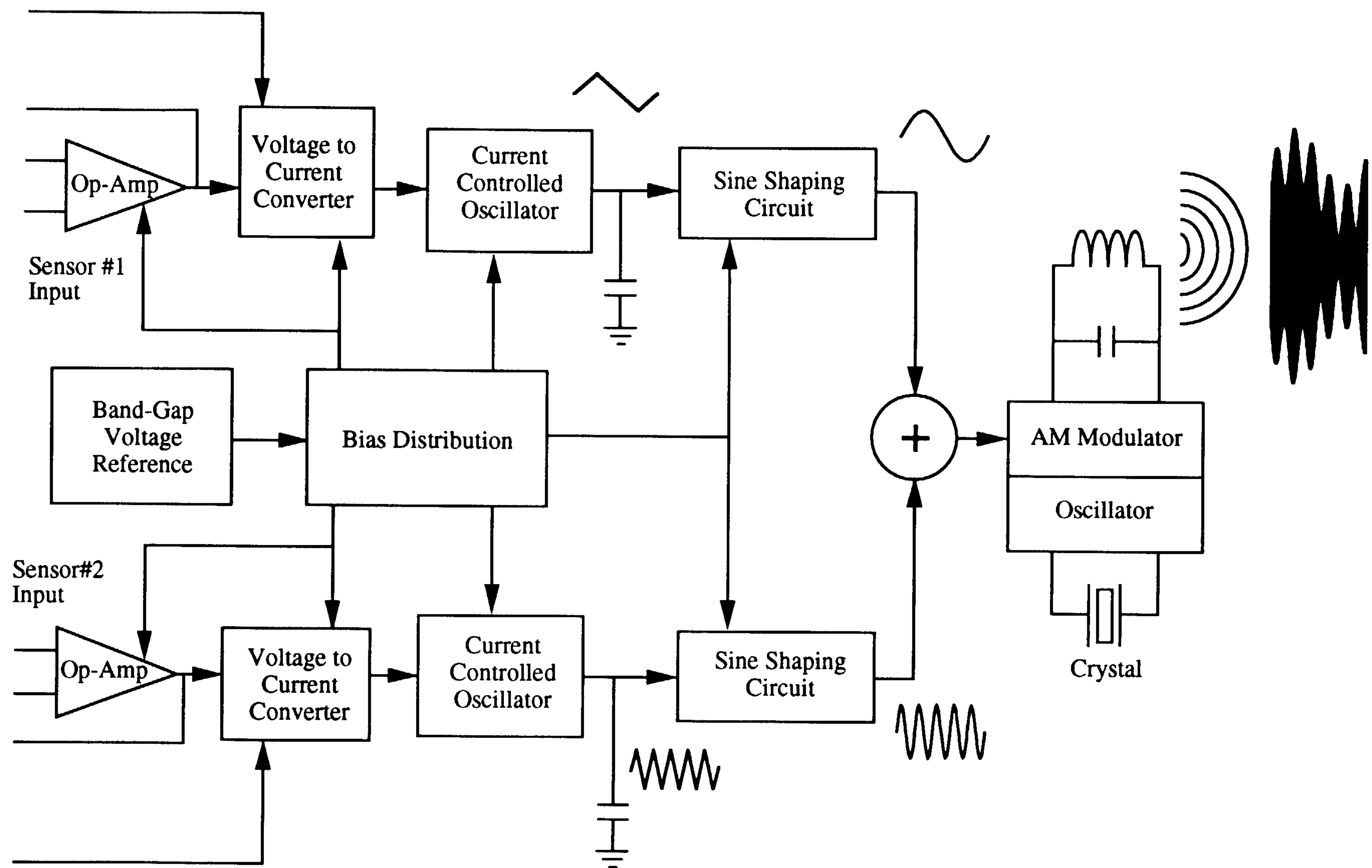

Figure 1. Telemetry chip block diagram

The current into the ICO programs the magnitude of the current through an external capacitor. This external capacitor is charged and discharged between two fixed voltages. When the capacitor voltage reaches one of the voltage trip points, the direction of the capacitor current is reversed. The resulting output of the ICO is a triangle wave between two voltages (nominally 400 mV and 800 mV) set by the band gap reference. Using voltages referenced to the band-gap reduces sensitivity to both supply voltage variations and temperature variations. The instantaneous frequency of the ICO output is described by equation 1:

$$f = (1.0 + Vd)/(0.8\ RC) \qquad (1)$$

where Vd is the differential voltage at the voltage to current converter input, R is 100 kΩ and C is the value of the external capacitor. Equation 1 shows that the signal of interest frequency modulates the ICO waveform. Frequency modulation allows constant voltages to be measured. The ICO's are designed for wide-band FM modulation in order to maintain dc accuracy. Constant voltages or currents are produced by a variety of sensors including strain gauges, chemical sensors and others.

The triangle wave contains odd harmonics of the ICO's fundamental frequency. The harmonics from the low frequency channel will fall in the band allocated to the high frequency channel and cause interference. Because of this, both of the channels are put through a sine shaping circuit. The sine shaping circuit substantially attenuates the odd harmonics present in the triangle wave. A shape circuit is used because it uses much less chip area than filter circuits, requires no external parts, and provides maximum flexibility for configuring the sub-carrier channels. The two shaped signals are summed to produce a combined signal that contains all of the information from the two sensors. The signals can be summed because the center frequencies and frequency deviations are chosen to limit the amount of cross-talk between channels.

The third channel is the temperature channel. The transducer is a temperature sensitive crystal which sets the frequency of the carrier oscillator. The carrier oscillator output is then amplitude modulated by the summed ICO signals. This final signal, which contains the two FM signals AM modulated onto the temperature signal drives a small coil which acts as an antenna. The coil generates a magnetic field that can be picked up by an external receiver. The temperature sensing crystal used to generate the AM carrier resonates at approximately 262 kHz at 25 °C and nominally varies 9 Hz/°C. The temperature measurement can be calibrated to better than 0.1 °C.

External Receiver

The received signal is picked up by a small ferrite core antenna coil and amplified by an automatic level controlled amplifier. Level control prevents the amplifier from saturating thus preserving the AM modulation when the pickup coil is close to the transmitter. When the transmitter is far away the automatic level control increases the gain so that the AM signal can be discriminated from the noise. The amplified antenna signal is split into two paths, one for temperature and one for the other sensors. The temperature signal is sent to a zero-crossing detector which feeds a computer controlled frequency counter. The other two channels are extracted by AM demodulating the signal received on the non limited antenna signal. This signal is equivalent to the summed signal in the internal system. Bandpass filters are used to extract the individual FM channels. The separated signals are then individually FM demodulated by phase locked loop circuits. A final filter to remove the FM carrier frequencies provides the measured physiological variables.

SYSTEM CONSIDERATIONS

Design Philosophy

Many of the design decisions were driven by the requirement that the final product be easy to manufacture. The custom IC was designed to use the minimum number of external parts in order to lower costs. The only external parts that must be separately assembled are the battery, sensors, ICO tuning capacitors, coil tuning capacitor, and the transmitter coil. Depending on the intended application there may also be gain setting resistors, signal conditioning capacitors, and other circuitry. This allows the user to customize inexpensive chips for different uses or for doing prototype work. If the volume of a particular application is high enough, some of the application specific circuitry could be integrated onto the chip to reduce costs. Another design consideration was to provide as many features as practical, while maintaining minimum chip area.

Practical Issues

The ICO center frequencies are determined by the nominal bias point of the input amplifier, the voltage to current converter reference voltage, the offset current, and the external capacitor. The offset current is determined by the band-gap voltage and an on-chip resistor. Because of the wide variation (± 30%) in the absolute value of the on-chip resistors, the ICO capacitors will generally have to be selected or trimmed in order to accurately set the center frequencies. Trimming the ICO center frequency also trims the frequency sensitivity of the ICO because the voltage to current converter uses an on-chip resistor that is matched to the resistor that sets the offset current. Applications that require low dynamic range and limited signal bandwidth may be able to use fixed value ICO capacitors.

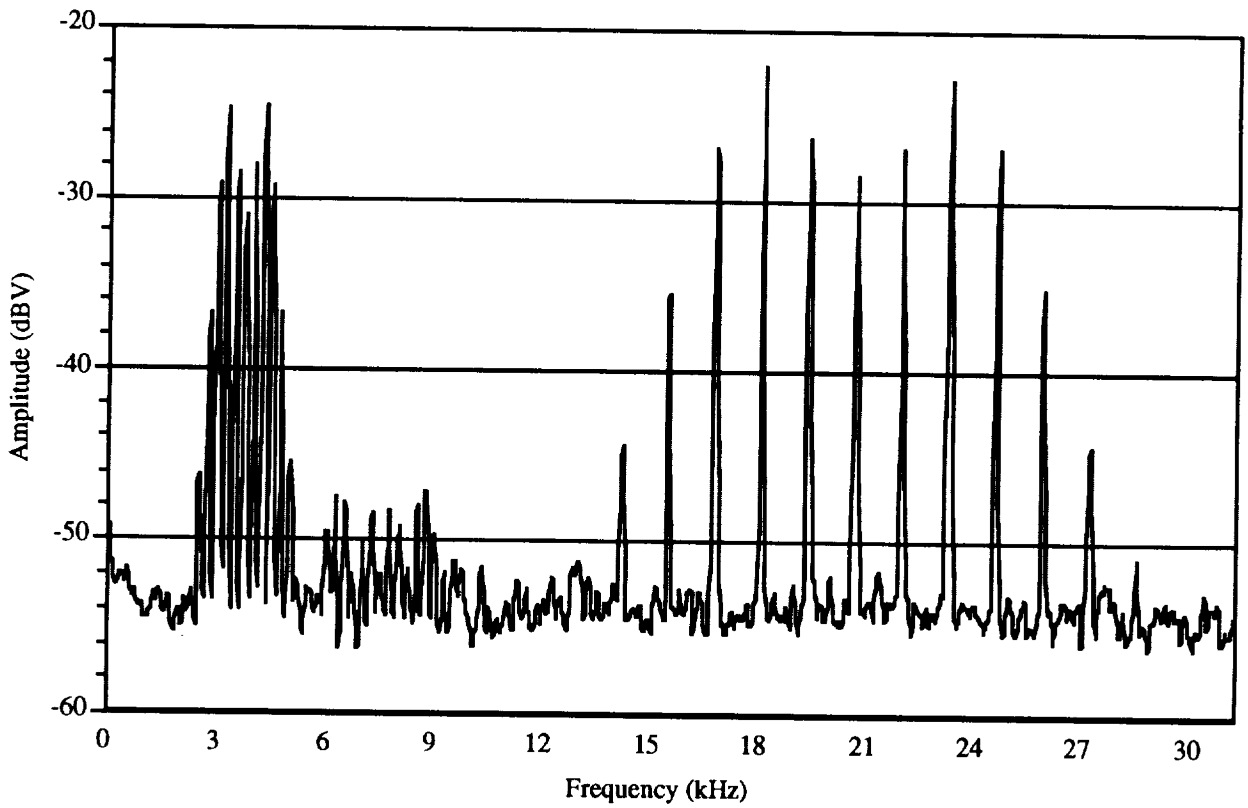

Figure 2. Frequency spectrum for summed FM channels under maximum bandwidth conditions.

Another possible trade-off is between signal bandwidth and dc accuracy. For wide bandwidth applications, the maximum frequency deviation of the ICO's should be around ± 20 % of the center frequency. This range allows the second harmonic caused by distortion in the sine-shaper and receiver circuits to fall outside of the passband of the FM signal, while still allowing for reasonable dc accuracy. Using ±20 % frequency deviation allows a total frequency error of 0.4 % not related to the input signal while maintaining a 1 % of full scale dc accuracy. Many different channel assignments are possible for this device. Our test system uses center frequencies at 3.8 kHz and 20 kHz. When modulated with maximum amplitude (± 20 % frequency deviation), maximum frequency (250 Hz and 1.3 kHz) inputs (corresponding to maximum channel bandwidth conditions) the measured frequency spectrum for the summed signal shown in Figure 2 results. Second harmonic distortion from the sine shaping circuit appears as a weak signal that falls between the passbands assigned to the channels. The sine shaping circuit minimizes the third and fifth harmonics in order to keep cross-talk to a minimum. Allowing larger than 20 % frequency deviation can improve the dc accuracy, because this tends to reduce the relative importance of battery voltage, and temperature on the center frequency. If the maximum frequency deviation is raised much beyond the 20% level there will still be little cross-talk, but the second harmonic distortion will fall into the signal's own passband resulting in distortion. This is not a problem for dc signals, and is unimportant if the amplitude of high frequency inputs is small.

The operational amplifiers have a variety of limitations. The input voltage range is from 800 mV below the battery voltage down to ground. The output voltage can cover the same range, but the gain drops and non-linearity increases when the output falls below 200 mV. The reference input range is the same as the op-amps, but behaves slightly non-linearly for voltages below 200 mV. A Schottky diode connected to ground and biased to a forward voltage drop of about 500 mV is available on the chip and can serve as a "virtual ground" for sensor connections. This "virtual ground" allows many types of sensors to be easily interfaced while maintaining the input and output signals above 200 mV. If the voltage to current converter is normally operated with zero differential input, then a change of 200 mV will cause a 20% frequency deviation. Some applications may benefit from having the voltage to current converter operate with a nominal differential voltage different from zero. This can either increase or decrease the change necessary for a 20% frequency deviation depending on the sign of the offset.

MEASURED CHARACTERISTICS

The measurements below represent data taken from 4 functional telemetry chips and generally reflect worst-case measurements.

Power Supply

Maximum supply currents is 690 μA at 2.5 V, 770 μA at 3.0 V, and 870 μA and 3.6 V. The transmitting coil current increases approximately linearly with increasing supply voltage, so that maximum transmission range is a function of supply voltage.

Input

Operational amplifier offset voltages from 8 amplifiers were 0.78, 0.36, 2.1, 6.1, -0.16, 0.87, -0.21, and 2.6 mV. This is too small a sample to realistically determine the bounds of the offset voltage, but it suggests that selecting devices with less than 1 mV offset voltages should be possible. Measured open loop gain was 850 minimum. The high frequency roll-off and slew rate limiting are well beyond the limits imposed on the signal bandwidth from considerations of the FM channel allocation. The offset voltage for the voltage to current converter circuits cannot be distinguished from the variation in offset currents added to the converter's output; however, based on the IC layout, it should be similar in magnitude to the op-amp offset voltage. The complete input circuit has a worst-case supply voltage to output current coefficient of 4.3 % /V, which limits either the range of useful battery voltage, or the dc accuracy of the signal transmission. For example, if a dc accuracy of 1 % is necessary , then the battery voltage should probably not be allowed to vary more than 100 mV over the course of measurement in order to leave room for other dc errors. This poor characteristic is the result of insufficient output impedance of the voltage to current converter. The circuit which performs the voltage to current conversion has been modified to improve this characteristic on the next generation chip.

Modulator

Maximum non-linearity for ICO output frequency verses differential input voltage for unity gain connected op-amp is less than 0.5 % of full scale for reference voltages from 800 mV below supply voltage down to 200 mV. The worst case non-linearity rises to 1% when the reference input is grounded. Severe non-linearity occurs for reference voltages above the specified input range. The maximum amplitudes of the harmonics at the output of the sine shaping circuit over the entire supply voltage range and ICO operating frequency range from 2 kHz to 25 kHz relative to the fundamental amplitude were: -20 dB for the second harmonic, - 29 dB for the third harmonic, -36 dB for the fourth harmonic, -38 dB for the fifth harmonic, all remaining harmonics were below -40 dB. The supply voltage coefficient of output frequency is dominated by the voltage to current converter coefficient for a total worst case of 4.3 %/V. The AM modulator circuit maintains the percent modulation between 50 % and 75 % over the power supply range.

Crystal Oscillator

The supply voltage coefficient of oscillator frequency was immeasurable. Variations of center frequency from unit to unit was no more than 2 Hz.

Transmitted Signal

Figure 3 shows the peak field strength of the transmitted signal from a coil having 300 turns in four layers 8.6 mm in diameter by 8.6 mm tall. The transmitter was operating with a nominal 3 V power supply. Range in a typical commercial environment is greater than 60 cm. Strong interfering signals can reduce the usable range. The transmitting coil current and field strength are proportional to supply voltage. This feature allows the power drain on the battery to diminish as the battery voltage falls resulting in slightly longer battery life. The test coil used in this measurement is applicable to ingestible applications where the telemetry system is packaged in a capsule form. Many other coil arrangements for different applications are possible.

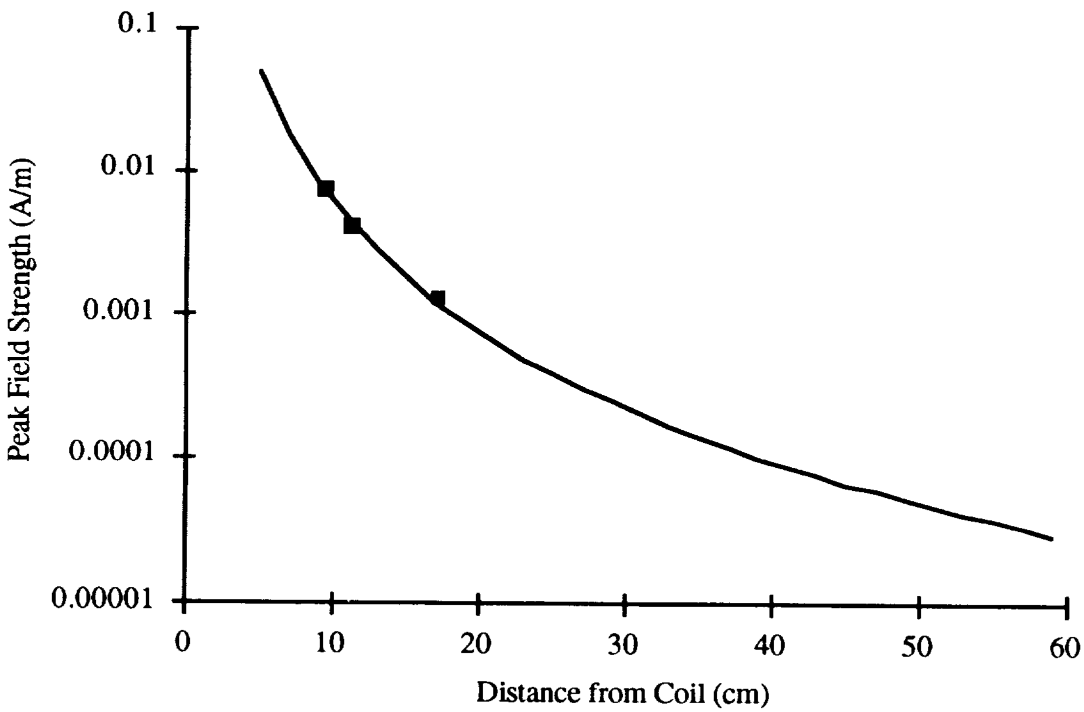

Figure 3. Axial field strength vs distance from coil. Symbols are measured values and curve is theoretical field strength.

Temperature Characteristics

The temperature coefficient of the FM channel center frequencies was + 0.48 %/°C, and was essentially equal to the temperature coefficient of the frequency sensitivity. This poor characteristic is basically the difference between the nominally 0.63 %/°C temperature coefficient of the on-chip 100 kΩ on-chip N-well resistor , and the nominally - 0.15 %/°C temperature coefficient of the external chip capacitors used in the test. This figure could be substantially improved by the use of N5700 dielectric capacitors, which will better compensate for the temperature variation of the on-chip resistors. Another possibility is to use a temperature correction algorithm on the received signal since the temperature of the telemetry system is always available. Future generation chips will probably utilize polysilicon resistors which use more chip area, but have only a + 0.09 %/°C nominal temperature coefficient in order to improve this characteristic.

EXAMPLE APPLICATIONS

Temperature is one variable that is always measured. The temperature transducer is a crystal that was designed to have a large linear frequency verses temperature characteristic. Because this transducer is required to generate the AM carrier for the other two channels, temperature is always available from the system.

One version of the telemetry system was customized to measure tendon force and the electromyogram of the muscle attached to the tendon. This implanted configuration used a strain-gage based force buckle to measure the tendon force. The experimenter could measure the amount of force, and muscle EMG produced by a given nerve stimulus. Such a device could be used to monitor the performance of a nerve stimulator.

Another example would be the measurement of pressure in the gastrointestinal tract. A capsule the size of a large vitamin pill could contain the telemetry system, pressure transducer, and a small battery. A bridge type pressure sensor could be used on one channel, while the other channel telemeters battery voltage in order to compensate for changes in excitation voltage. An ingestible sensor of this type could measure peristalsis of the gut, and also can pick up the respiratory rate.[1]

Another application could measure the partial gas pressures of oxygen and carbon-dioxide in the gastrointestinal tract, also in the form of a swallowable capsule. CO_2 and O_2 electrodes inside the pill could measure gas concentrations that diffuse through the silicone rubber outer coating of the pill. This measurement could be useful in detecting ischemia of the gastrointestinal tract. When blood flow to the gut is reduced, carbon dioxide builds up and oxygen is depleted from the tissues. These gasses diffuse through the tissues, so the ambient concentration of these gases in the lumen of the gut change with ischemia.[2]

The system is not limited to biological measurements. It could be modified to transmit data from any container whose integrity must be maintained. An example is a pressure gauge for vacuum systems that does not require a feedthru in the chamber. The pressure transducer would be interfaced to the telemetry chip and then the signal transmitted through one of the chamber viewing ports. The other channel could be used to transmit an analog or digital signal from the experiment in the chamber.

CONCLUSIONS AND FUTURE PLANS

A very small telemetry system has been designed and tested. The system is ready to be integrated with existing sensors to produce a device customized for a specific need. A hybrid substrate is being designed to make the final outline of the ingestible device as small as possible. The projected dimensions of the ingestible device are 9 mm diameter by 15 mm long.

A version of the chip which is currently under production contains new digital functions to send a calibration/identification signal to the external receiver. With the calibration embedded in the data stream the receiver will automatically read it and apply it to the data. The calibration factors are added at the factory and are stored in the telemetry chip until it is activated. Other changes include a band-gap regulated output voltage for sensor excitation, various circuit improvements to reduce power consumption and increase power supply rejection ratios, and on-chip power on/off circuitry. Many other future improvements are planned for this device including the ability to operate from a single 1.5 V battery.

Acknowledgement

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