SMART DUST MOTE FORERUNNERS

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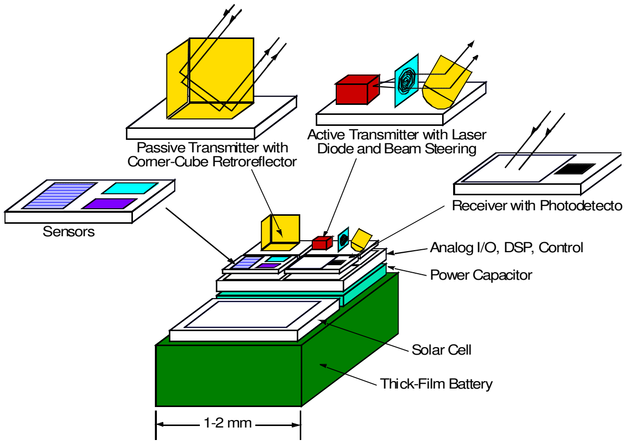
ABSTRACT

We have demonstrated a 138mm^3 autonomous uni-directional sensing/communication mote that optically transmits a measure of the ambient light level. We have also developed a 63mm^3 autonomous bi-directional communication mote that receives an optical signal, generates a pseudorandom sequence based on this signal to emulate sensor data, then optically transmits the result, although it has only been demonstrated in a bench configuration at this time. The latter system contains a micromachined corner cube reflector, a 0.078mm^3 CMOS chip that consumes 75µW, and a Mn-Ti-Li cell, but we have also demonstrated operation from an ~2mm^2 solar cell. These motes allow us to demonstrate necessary concepts of Smart Dust such as optical data transmission, data processing, energy management, miniaturization, and system integration.



igure 1. *Smart Dust conceptual diagram.*

INTRODUCTION

The Smart Dust project[1] aims to explore the limits of system miniaturization by packing an autonomous sensing, computing, and communication node into a cubic millimeter mote that will form the basis of massive distributed sensor networks, thus demonstrating that a complete system can be integrated into 1mm^3. Because of the discreet size, substantial functionality, connectivity, and expected low cost, Smart Dust will enable entirely new methods of interacting with the environment, providing more information from more places in a less intrusive way than ever before. Some examples of applications that we are pursuing include defense networks that could be rapidly deployed by unmanned aerial vehicles (UAV), tracking the movements of birds, small animals, and even insects, fingertip accelerometer virtual keyboards, monitoring environmental conditions that affect crops and livestock, inventory control, product quality monitoring, smart office spaces, and interfaces for the disabled.

Smart Dust will require both evolutionary and revolutionary advances in miniaturization, integration, and energy management. These advances will be facilitated by the progress in MEMS, which allows us to build small sensors, optical communication components, and power supplies; and microelectronics, which provides increasing amounts of functionality in smaller areas and with lower energy consumption. Figure 1 shows the conceptual diagram of a Smart Dust mote[1]. The power system may consist of a thick film battery and/or a solar cell with a charge integrating capacitor for periods of darkness. A variety of sensors, including light, temperature, vibration, magnetic field, acoustic, and wind shear, can be integrated on the mote depending upon the mission. An integrated circuit will provide sensor signal processing, communication, control, data storage, and energy management. A photodiode will allow optical data reception, while two transmission schemes are being explored: passive transmission using a corner-cube retroreflector (CCR)[2] and active transmission using a laser diode and steerable mirrors[3].

Because of the small size of the mote, energy management is a key constraint of the design. Current battery and capacitor technology can store approximately 1J/mm^3 and 10mJ/mm^3, respectively, while solar cells can provide about 1J/day/mm^2 in sunlight and 1-10mJ/day/mm^2 indoors. Energy consumption must therefore be minimized in every part of the system. We estimate that our optical receiver will consume 0.1nJ/bit, the transmitter will use 1nJ/bit, the analog to digital converter will require 1nJ/sample, and computations are anticipated to consume under 1pJ/instruction.

In order to test the concepts of Smart Dust, such as the communication link and integration issues, we designed two preliminary platforms that implement primitive functions of a dust mote. The first mote optically transmits a sensor reading, while the second decodes an incoming optical signal, generates simulated sensor data via a pseudorandom number generator, and drives a CCR with this data to passively transmit information by modulating the reflection of the incoming interrogation beam. These systems are precursors to a fully autonomous sens-

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[1] "And why beholdest thou the **mote** that is in thy brother's eye, but considerest not the beam that is in thine own eye?" *Matthew 7:3 (KJV)*

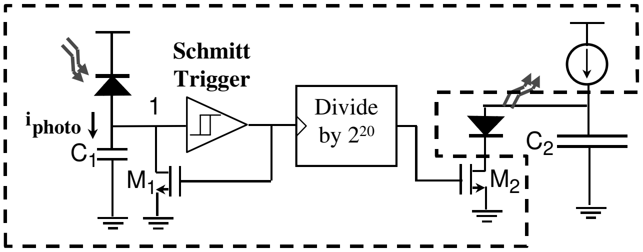


Figure 2. *Diagram of the circuit on the mote in figure 3. The components in the dashed box are integrated on the CMOS ASIC.*

ing, computing, and communications platform for Smart Dust distributed sensor networks.

UNI-DIRECTIONAL SENSING MOTE

The first Smart Dust mote forerunner provides a demonstration of transmitting sensor data from a tiny autonomous device. The system (figure 2) consists of a 0.35µm CMOS ASIC with an on-chip photodiode whose photocurrent proportionally sets the frequency of a relaxation oscillator. As the photocurrent charges up C_1, the voltage on node *1* will eventually reach the turn-on voltage of the Schmitt trigger buffer, whose output will then rapidly switch high. This will cause *M1* to turn on, discharging C_1 and causing the Schmitt trigger buffer to turn off again. The frequency at which this cycle takes place is determined primarily by the charging time: $\tau = C_1 (V_{M+}/i_{photo})$, where V_{M+} is the Schmitt trigger low to high threshold and i_{photo} is related to the incident optical power P by $i_{photo} = \eta\ (\lambda_0/1.24)P$ with η being the quantum efficiency of the photodiode. For reasonable sizes of integrated capacitors and typical photocurrents, the oscillation frequency would be out of the region of interest, so the output of the Schmitt trigger is run through a divide by 2^{20} circuit. This signal in turn drives *M2*, which for the case shown in figure 2 sinks current from an LED to turn it on. Since the internal resistance of the button cells used to power this mote is too high to directly drive the LED, an external capacitor (C_2) integrates the charge from an on-chip current source to build up enough to pulse the LED. For a passive transmission scheme, a battery stack large enough to actuate the CCR would be connected to one electrode of the device, while the other electrode would be connected to the drain of a cascode transistor on *M2* that facilitates switching the high voltage. When *M2* turns on, the electrode would be pulled to the negative terminal of the battery, causing the CCR to switch on. This results in a passive or active transmission that flashes in proportion to the incident light level.

The resulting mote is shown in figure 3. It is currently operated from a 6.8mmOD x 1.2mm, 3V, rechargeable Mn-Li cell, yielding a 138mm^3 (circumscribed cylindrical volume) mote that draws 14-124µW (figure 4). The period ranges from over 30 seconds in total darkness to ~300ms in sunlight (figure 5). Furthermore, it utilizes a surface mount resistor to bias the current source, a 15µF surface mount capacitor to integrate the charge from the current source, and a green LED. A knife switch formed from bent pieces of metal allows the mote to be turn on when a piece of wire is dropped into the terminal. This hybrid system is held together with silver epoxy and manually wire-bonded.

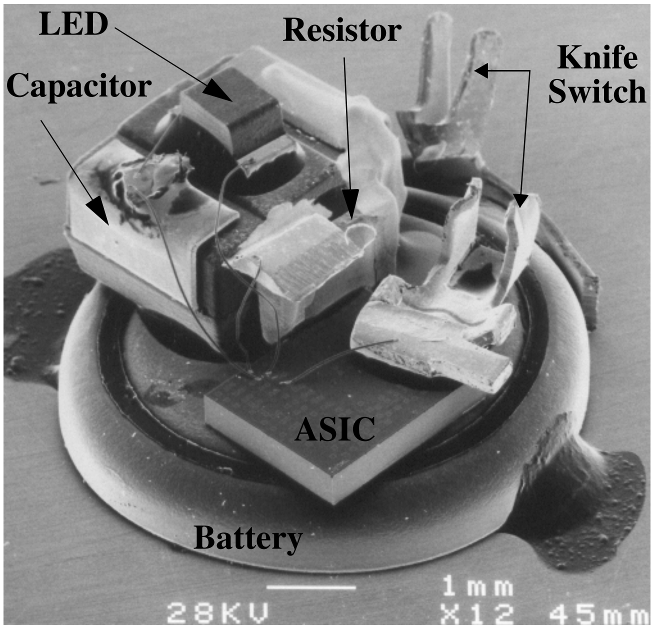
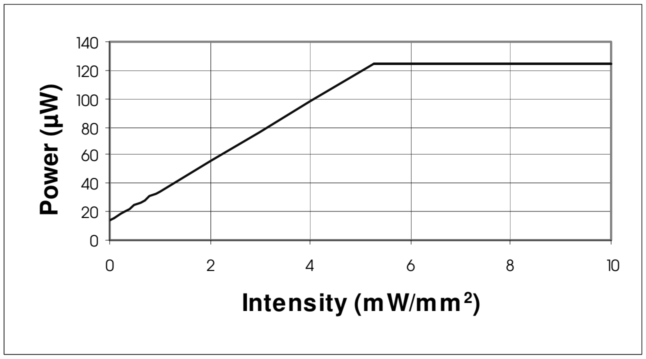
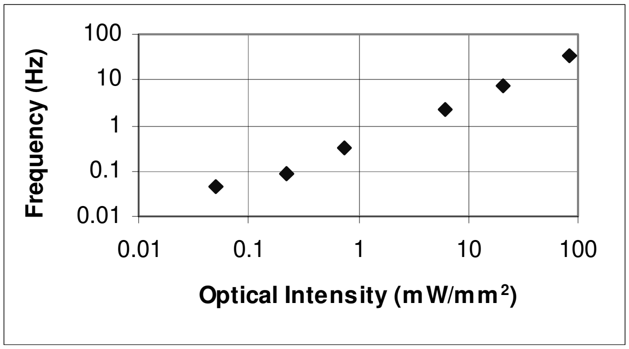


Figure 3. *138mm^3 mote with light intensity dependent emissions. In this system, a resistor, 15µF capacitor, knife switch, green LED, and 0.35µm CMOS ASIC containing a photodiode, relaxation oscillator, frequency divider, current source, and current sink FET are mounted onto a 3V Mn-Li button cell.*



igure 4. *Power consumption as a function of incident light ntensity for the the mote in figure 3.*



igure 5. *Measured flashing frequency vs. incident optical ntensity for the mote in figure 3.*

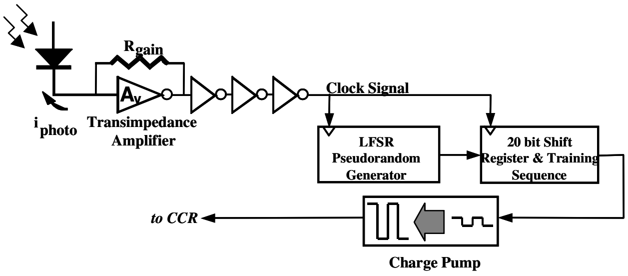


Figure 6. *Diagram of the circuit on the CMOS ASIC in figure 7.*

BI-DIRECTIONAL MOTE

The second Smart Dust mote forerunner[4,5] provides a demonstration of bi-directional communication with a tiny autonomous device. The system is interrogated by a periodic laser signal. An integrated photodiode (figure 6) converts the laser signal into a photocurrent that is amplified and thresholded by the transimpedance amplifier to generate a rail-to-rail binary signal that is used as a system clock. The clock signal drives a pseudorandom sequence generator that produces a data stream which is fed into a charge pump to multiply the voltage up to 8V. This signal is then sufficient to actuate the micromachined CCR, which modulates the interrogating laser beam. The reflected signal is received by an optical imager that can extract the signal from many motes simultaneously, providing a form of spatial division multiple access (SDMA).

The ASIC in this system is fabricated in a 0.25µm CMOS process in order to minimize energy consumption of the parasitic capacitances. The integrated 0.04 mm^2 photodiode is formed from a P+/N-well junction that has a quantum efficiency of 0.057 in this process, providing a responsivity of 0.029 A/W at 632nm. N-well/P-substrate diodes have actually been measured to be more effective with a quantum efficiency of 0.73 and a responsivity of 0.37 A/W at 632nm, so they will be used in the future. The photocurrent is conditioned by a transimpedance amplifier[6] that features a small size and is self-biasing. The amplifier consists of a single inverter with a PMOS transistor in the feedback loop for the transimpedance stage and a set of three series inverters to amplify and buffer the signal. However, this amplifier's optical threshold is not self-adjusting but is dependent on the supply voltage. The power consumption and gain are also not well controlled. The gain of the amplifier is set at approximately 100MΩ so that saturation of the output signal occurs for a small range in input current, typically a few nA. With 670nW of 632nm light incident on the photodiode generating 19nA of photocurrent, the entire receiver was measured to consume 84µW (84nJ/bit) at 1kbps and V_{dd}=1.4V. The receiver has been measured to operate with less than 13nA of photocurrent and occupies 152µm^2.

The binary signal from the optical receiver is used to clock an 8-bit linear feedback shift register (LFSR), generating a pseudorandom serial sequence that is sent through a 20 bit shift register (SR) preset to a training sequence. The training sequence is a standard 0101... pattern that allows the base station imaging receiver to set its detection threshold and maximum likelihood detector coefficients. A version of the LFSR/SR was designed with standard cells utilizing a single-phase pseudo-static logic style targeted at 50-200MHz operation in the 0.25µm process that requires 26,300µm^2 and has a measured average power of 5.25nW at 1.4V and 1kbps (5.25pJ/bit) with a leakage current of 440pA. A custom version utilizing ultra-low power digital techniques[7], including fully static, race-free flip-flops, minimum sized devices, and branch-based layout to facilitate merged diffusion, achieves a simulated average power of 600pW (600fJ/bit) at 1.4V and 1kbps in 12,300 µm^2, showing that significant gains can be made at the circuit and layout levels. The custom version is currently being tested.

The data stream generated by the LFSR/SR is transmitted via a CCR, which is a device consisting of three orthogonal 250µm-square micromirrors: two that are fixed and one that can be moved electrostatically. A beam of light passed into the corner formed by the three orthogonal plates will be reflected parallel to the incident beam. When the movable plate is not orthogonal, the reflected beam will not be parallel to the incident wave. By toggling the movable plate in and out of the orthogonal position, an imager that detects the reflected light parallel to the transmission source will record a series of flashes. In this manner, data can be passively transmitted back to the base station, which consists of the laser for data transmission and an optical imaging array for acquisition of the flashing pulses. The solid angle over which the CCR can communicate is somewhat less than an octant. Four devices can be fabricated on a single chip in order to communicate to the greater portion of a full hemisphere.

Because the plate is electrostatically actuated, this device enables a very low power, passive transmission scheme. The CCR is currently fabricated in the Cronos MUMPS three-layer, 2µm polysilicon micromachining process. The mirror requires 8V to be actuated and has been measured to operate up to 118bps, although the pull-down voltage and actuation speed can be traded off in the design process. The capacitance from the actuated mirror to the electrode is 308fF, but the bond pad and other parasitics increase the total capacitance on the node to 21pF, resulting in an energy consumption of 670pJ/bit, which compares favorably with other transmission schemes such as Bluetooth (100nJ/bit). The CCR has been demonstrated to operate over 150m but is expected to reach up to 1km.

Since the CCR requires 8V for actuation, but the circuits are run from a single 1.4-1.5V button cell, the data stream from the LFSR/SR is sent through a charge pump voltage multiplier that produces a signal that swings from 0 to 8V. The charge pump uses a configuration of PFETs in individual N-wells to reduce the back gate effect[8]. Each stage contributes an increase of V_{dd} and the amplification is then limited to the breakdown voltage of the N-well/substrate junction -- roughly 20V. The design utilizes eight charge pump stages each with 100fF and 300fF poly-poly capacitors. The charge pump block also includes an 11-stage current starved ring oscillator with a four-phase clock generator. It consumes a measured 14µW while charging and has an area of 12,800µm^2.

Figure 7 shows a mock-up of the system. The entire circuit, including a power-on reset RC network, uses a die area of 300x360µm^2, consumes 75µW at 40Hz (the maximum speed of the laser used in the test), and is mounted next to the CCR on a 5.8mmOD x 1.6mm, 1.5V, rechargeable Mn-Ti-Li cell, yielding a complete two-way communication system in 63mm^3. The ASIC has also been operated from an ~2mm^2 solar cell under incandescent lighting. The entire system has been successfully demon-

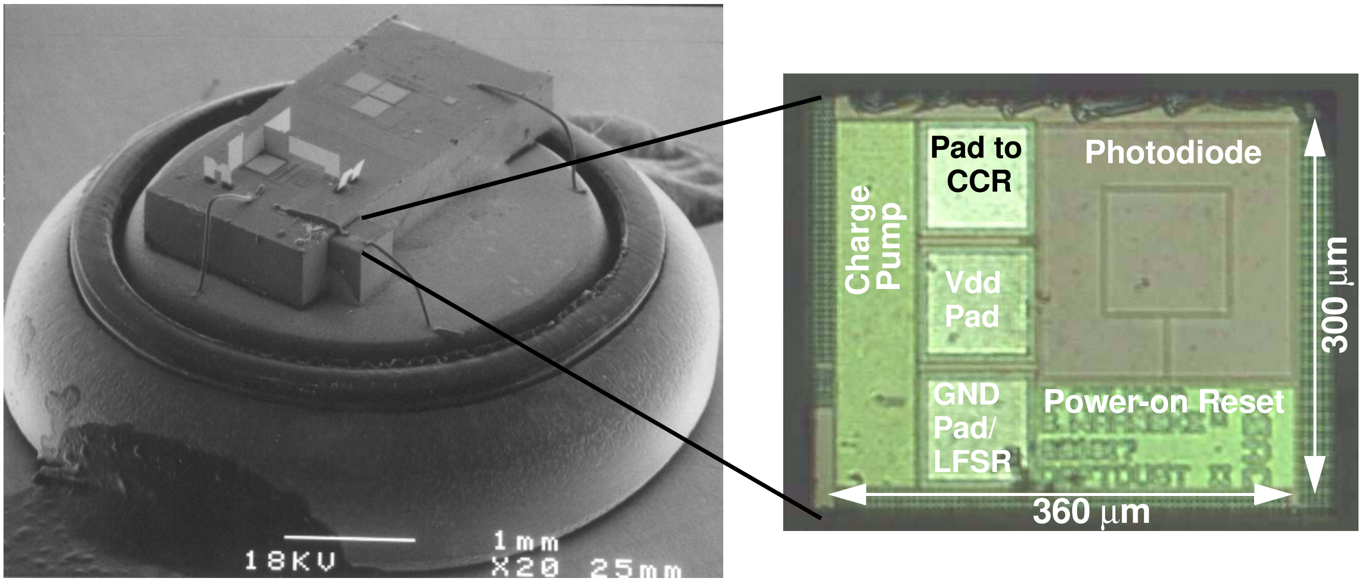


Figure 7.*Autonomous bi-directional communication mote with a MUMPS optics chip containing a corner cube retro-reflector (CCR), a CMOS ASIC for control, and a1.5V Mn-Ti-Li rechargeable button cell for power. The total circumscribed cylindrical volume is 63 mm*^{3}*. The SEM on the left shows two CCRs on the left-hand die: the one in the foreground is assembled while the one in the background is unassembled. This mote is a mock-up demonstrating how the system may eventually be assembled, which is why not all the pads are bonded. The CMOS ASIC on the right is 300x360μm with photodiode, receiver, LFSR, power-on reset, and charge pump; the digital circuits are under the GND pad, while the other circuits are placed under metal shields to eliminate photo-generated carriers.*

strated on the laboratory bench, but it remains to be demonstrated in the compact format shown in figure 7.

CONCLUSION

We have demonstrated a 138mm^3 autonomous uni-directional sensing/communication mote that optically transmits a measure of the incident light level. Furthermore, we have demonstrated an autonomous bi-directional communication mote that receives an optical signal, generates a pseudorandom sequence based on this signal to emulate sensor data, then optically transmits the result, and can be packaged in 63mm^3. These motes demonstrate necessary concepts of Smart Dust.

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