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Micro-Miniature Radio Frequency Transmitter for Communication and Tracking Applications

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DISCLAIMER

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ABSTRACT

A micro-miniature radio frequency (rf) transmitter has been developed and demonstrated by the Oak Ridge National Laboratory. The objective of the rf transmitter development was to maximize the transmission distance while drastically shrinking the overall transmitter size, including antenna. Based on analysis and testing, an application-specific integrated circuit (ASIC) with a 16-GHz gallium arsenide (GaAs) oscillator and integrated on-chip antenna was designed and fabricated using microwave monolithic integrated circuit (MMIC) technology. Details of the development and the results of various field tests will be discussed.

The rf transmitter is applicable to covert surveillance and tracking scenarios due to its small size of 2.2 × 2.2 mm, including the antenna. Additionally, the 16-GHz frequency is well above the operational range of consumer-grade radio scanners, providing a degree of protection from unauthorized interception. Variations of the transmitter design have been demonstrated for tracking and tagging beacons, transmission of digital data, and transmission of real-time analog video from a surveillance camera. Preliminary laboratory measurements indicate adaptability to direct-sequence spread-spectrum transmission, providing a low probability of intercept and/or detection. Concepts related to law enforcement applications will be presented.

Keywords: beacon, transmitter, microwave, MMIC, ASIC, GaAs

1. INTRODUCTION

The Instrumentation and Controls Division of Oak Ridge National Laboratory (ORNL) has developed a micro-miniature radio frequency (rf) transmitter. The device is an rf successor to a pulsed-mode miniature infrared (IR) transmitter previously developed for field studies of Africanized bees.[1] The focus of the rf transmitter development was to maximize the transmission distance while drastically shrinking the overall transmitter size, including an on-board antenna. A theoretical analysis was conducted to identify an antenna geometry that could be miniaturized and fabricated using standard integrated circuit technology. Based on this analysis, an application-specific integrated circuit (ASIC) with a 16-GHz gallium arsenide (GaAs) oscillator and integrated on-chip antenna was designed, fabricated, and tested. This paper addresses the design of the transmitter and describes implementations directly applicable to law enforcement applications.

2. ANTENNA DEVELOPMENT

A major design goal of the transmitter development was to make the entire system as small as possible. Because no size advantage would be gained from designing a miniature transmitter that attached to a large external antenna, the first design goal was to determine if the antenna could be fabricated onto the integrated circuit (IC) chip. A theoretical analysis with extensive modeling was performed with the objective of maximizing the transmission distance while fitting the antenna onto the same chip as the active electronics.

Several assumptions were made concerning the transmitting frequency, maximum transmitting antenna size, available rf drive to the transmitting antenna, and the receiving antenna. The transmission frequency was limited to less than 20 GHz, primarily because usable transistor gains at higher frequencies were not obtainable from readily available semiconductor processes. Another frequency constraint was to avoid the microwave-absorption bands in the atmosphere. The size of the transmitting antenna was constrained to a maximum of 2.2×2.2 mm, based on the dimensions of a standard semiconductor chip. The antenna drive stage was limited to a performance envelope of either 5 V or 50 mA, whichever was reached first. Additionally, a 60-cm parabolic dish receiving antenna was chosen because one was readily available in our organization.

Various antenna configurations were modeled to determine the radiation resistance when implemented as an electrically short antenna. Two configurations that showed promise were the loop antenna and the capacitively-loaded dipole, also called an "inverted-L". Simulations indicated that the loop antenna would be the best choice for frequencies above 25 GHz when operated within the other constraints. Because this frequency exceeded the 20-GHz semiconductor process limitation, the inverted-L was selected for the design. Simulations of the inverted-L antenna indicated that a performance peak occurred in the frequency region around 16 GHz, which was within the original constraints. Additionally, the calculations indicated that a transmission range of approximately 3 km could be obtained when using the 60-cm receiving antenna.

Several prototype antennas were fabricated onto GaAs substrates in both the loop and inverted-L configurations to experimentally verify the analytical results. Field strength measurements were made for the two antenna configurations using a microwave generator as a transmitting source and a spectrum analyzer as a calibrated receiver. Polar-coordinate plots were made for the field strength of the two antenna configurations. Test results indicated that the inverted-L provided performance consistent with the theoretical predictions. The next step was to design a transmitter to operate with the antenna.

3. RF CHIP DEVELOPMENT

Results of the antenna development phase indicated that an operating frequency in the 16-GHz range was optimum for the inverted-L antenna. Operation at this frequency necessitated the use of a GaAs semiconductor fabrication process for the electronics. An additional benefit of GaAs technology is that the conductivity of GaAs is much lower than for a silicon substrate, thus reducing the rf losses into the substrate when the antenna is fabricated directly on the chip.

The "HA" process from TriQuint Semiconductor was chosen to implement the transmitter with on-chip antenna. The HA process supports transistor gate lengths as small as 0.5 micron, which produces transistors with a current gain-bandwidth product of 21 GHz. The process offers two layers of metallization for signal routing. The first layer is deposited on the surface of the GaAs substrate. The second layer is constructed from support post structures under an elevated metal layer that forms an "air-bridge" for crossing over other traces. The inverted-L antenna was constructed in the air-bridge layer because it slightly elevated the antenna structure above the substrate and further reduced the substrate losses.

The oscillator circuit was implemented as a symmetrically balanced, push-pull, negative-resistance topology. The transistor gate input impedance resonates with on-chip gate inductors to produce a real part of the gate input impedance that is sufficiently negative to sustain oscillation. On-chip inductors and capacitors are implemented as a resonant tuned circuit in the transistor drain path to determine the frequency of oscillation. Additionally, a voltage-dependent capacitance is implemented in the form of a reverse-biased gate/channel metal semiconductor field effect transistor (MESFET) operating as a varactor diode. This voltage-dependent capacitance makes the frequency of the oscillator adjustable based on a control voltage, thus producing a voltage controlled-oscillator (VCO). The rf output from the oscillator is coupled to the antenna through on-chip inductors that match the antenna impedance to the drive electronics. Additionally, a gate/channel MESFET diode is included on the chip to provide a method of measuring the temperature of the circuitry for compensation of temperature effects on the oscillator frequency.

The completed 2.2 × 2.2 mm GaAs microtransmitter chip is shown in the microphotograph of Fig. 1. The symmetrical inverted-L antenna can be seen across the top and two sides of the chip. The transmitter electronics are positioned in the central portion of the chip, and electrical connections for power, VCO input, and chip temperature measurement are brought out on the bonding pads shown at the bottom of the photograph.

4. ANTENNA PATTERNS

Far-field antenna pattern measurements were conducted to characterize the rf radiation performance of the electrically short antenna fabricated on the GaAs chip. Additionally, the microtransmitter with on-chip antenna was characterized for several mounting and packaging configurations.

Because both dielectric and metallic materials in the near-field region of the antenna affect the radiation pattern, the results differ from the pattern of an ideal dipole antenna. The measurement system included a spectrum analyzer for the test receiver, a 60-cm parabolic receive antenna, and a tripod with a rotational platform to hold the transmitter substrate in the appropriate orientations.

The antenna patterns were sampled in 15° increments for each rotational plane. Electromagnetic fields were measured for both horizontal and vertical polarizations for each of the transmitter orientations. Representative samples of the resulting characterizations for the horizontally-polarized case are shown in the polar plots of Fig. 2. These antenna pattern measurements are presented as polar-coordinate plots with the amplitude scale normalized to 0 dB. The plots illustrate the directional properties of the transmitter antenna coverage and provide a peak-to-null performance measurement. The peak-to-null ratio of the directional pattern will scale appropriately for other receiving systems, with the absolute range increasing as the receiver performance improves.

Figure 2 (a) shows the antenna pattern as measured in the plane of the transmitter chip. The rf chip characterized in this plot is mounted on a ceramic substrate with additional components that affect the field pattern. The best performance is on the side of the substrate with the rf chip antenna outward (180°), which is consistent with theoretical dipole performance. A 14-dB null is introduced at 330° by a metallic electronic component mounted on the ceramic substrate. Additional minor signal cancellations at other angles result from other electronics components on the substrate.

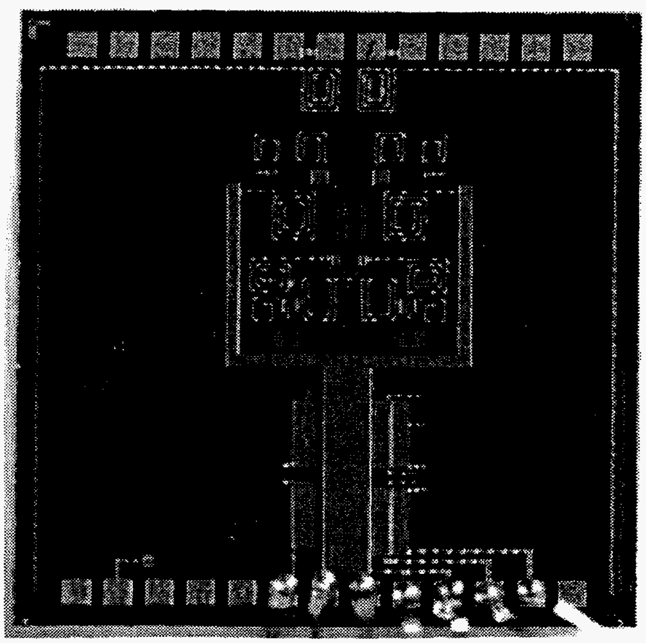
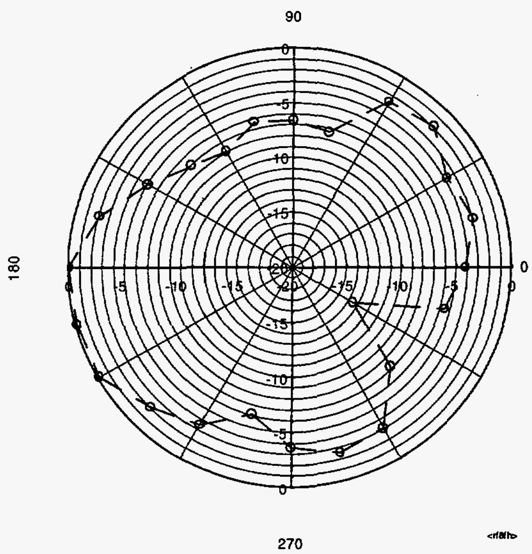
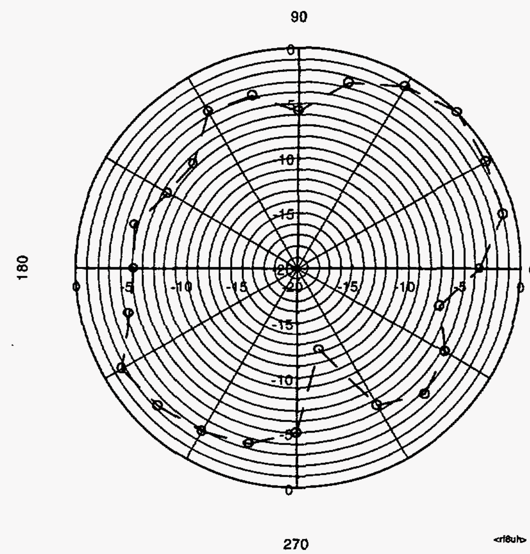


Fig. 1. Photomicrograph of GaAs transmitter chip.



RF Beacon Antenna Pattern
16.34 GHz, Coplanar, Horizontal
(a)



RF Beacon Antenna Pattern
16.34 GHz, Perpendicular, Horizontal
(b)

Fig. 2. Horizontally-polarized antenna response for two orientations.

The antenna pattern for an upright (vertical) transmitter orientation is shown in Fig. 2(b). The transmitter chip and antenna have minimal blockage from metallic components and should therefore produce a field radiation pattern close to that of a horizontal dipole. The major pattern lobes around 45° and 210° are rotationally shifted from the 0° and 180° response of an ideal dipole. Dielectric effects of the ceramic substrate are likely responsible for this field rotation. The antenna nulls occur at 135° and 285°, again consistently rotated from the expected 90° and 270°. Overall, this configuration performed like a phase-rotated dipole antenna with shallow nulls because the dielectric effects of the substrate cause a "smearing" of the phase.

5. TRANSMITTER FIELD TESTING

Early field testing of the prototype microtransmitter was conducted using one of the rf transmitter chips and a battery installed in a plastic bottle. This prototype "pill bottle" transmitter is shown in Fig. 3. The device operated in continuous wave (CW) mode and provided a convenient configuration for testing the transmitter under simulated field scenarios. The transmitter was operated under a variety of conditions to determine transmission range and susceptibility to shielding from structures between the transmitter and receiver. Experimental scenarios included transmitter tracking of pedestrians and vehicles, location of the transmitter within buildings, and a distance test to verify the usable range of the signal. A signal-to-noise ratio of 10 dB was considered acceptable for tracking the transmitter.

A primary limiting factor of microwave system performance is the requirement that near line-of-sight conditions must be maintained between the transmitter and receiver, although a visual path is not necessary. Even though the 16-GHz microwave frequency does not propagate efficiently over hills or around corners, some reflected signal can be received around corners in dense urban areas and thus provide a sense of direction towards the transmitter. This frequency is subject to signal attenuation from dense building structures or thick clusters of vegetation with a high moisture content, but signal levels of tests performed in moderate rain varied little from those in clear weather.

Pedestrian tests consisted of placing the transmitter into a person's pocket or purse and allowing the person to move along a sidewalk or road while being tracked by the receiver. Experiments of this type were performed at ranges up to 1.5 km, with terrain rather than signal strength limiting the distance. True visual contact between the

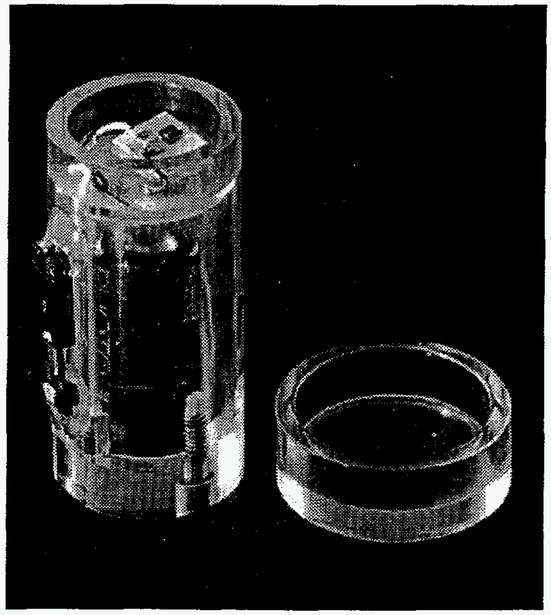


Fig. 3. Prototype CW microtransmitter.

transmitter and receiver was not required, provided that the interfering structures were not extremely dense. Wooden and brick-veneer structures had little effect on the signal, while massive concrete and steel structures increased the signal attenuation and shortened the reliable range.

A vehicle test consisted of placing the transmitter into various areas of the vehicle and tracking the transmitter while the vehicle was in motion. Tests of this type were conducted using cars, trucks, and vans over a 1.5 km range, with the limiting factor again being terrain. Scenarios were executed placing the transmitter in such locations as the front seat, floor, glove compartment, and spare tire well. The windows of the vehicles provided large apertures through which the microwave energy could escape, and tracking the vehicle presented no problem when line-of-sight was maintained. Likewise, the rubber gasket around the car's trunk lid provided a slot aperture through which the microwave energy escaped from the vehicle's trunk. The transmitter signal would be lost when the vehicle went behind a hill or massively thick building, but the general direction of the vehicle could still be obtained using reflections.

The building tests were performed by placing the transmitter on a person (pocket or purse) and allowing the person to move through the building while being tracked from a fixed receiver. A successful test was achieved by setting the receiver approximately 50 m from a two-story brick-veneer office building and identifying the location of the transmitter as it was moved through various rooms of the building. The position of the transmitter could be pinpointed to each individual office within the building. Additional tests were performed in a large masonry building and tracking could again be successfully accomplished, provided the signal was not required to penetrate more than three or four masonry walls.

A final scenario consisted of a long-range distance test. The terrain around ORNL is comprised of numerous hills and valleys which make long-distance testing difficult, as indicated by the 1.5 km limit on the pedestrian and vehicle tests. Two accessible hilltops were identified with a separation distance of 3 km. The transmitter was positioned on one hill while the receiver was placed on the other. The signal-to-noise ratio obtainable at that range was 10-20 dB depending upon the placement of the transmitter with respect to buildings and trees. Placing the transmitter directly on the ground produced a signal-to-noise ratio of 5-10 dB from that range.

These demonstrations indicate that the transmitter is suitable for tracking applications in situations where no major hills or obstacles are between the transmitter and receiver. Tracking within buildings is feasible provided that the building construction does not contain massive amounts of electromagnetic shielding or lossy materials.

6. APPLICATIONS TO LAW ENFORCEMENT

A micro-miniature rf transmitter of the type described in this paper establishes an enabling technology for numerous devices supporting the law-enforcement arena. As described in the field tests, the transmitter can be used for tracking and tagging operations for people, vehicles, or objects. A pulsed-carrier version of this transmitter, optimized for tagging operations, is shown in Fig. 4. The transmitter chip was mounted on a 1 cm^2 ceramic substrate along with a custom-designed control chip, crystal, and other electronic components as shown on the right side of the figure. An encapsulated unit with power leads is shown on the left side. This tagging device requires a power source that provides 6 V at 20 μA. The low current requirements of this transmitter permit long-term operation from either micro-miniature solar cells or wristwatch batteries.

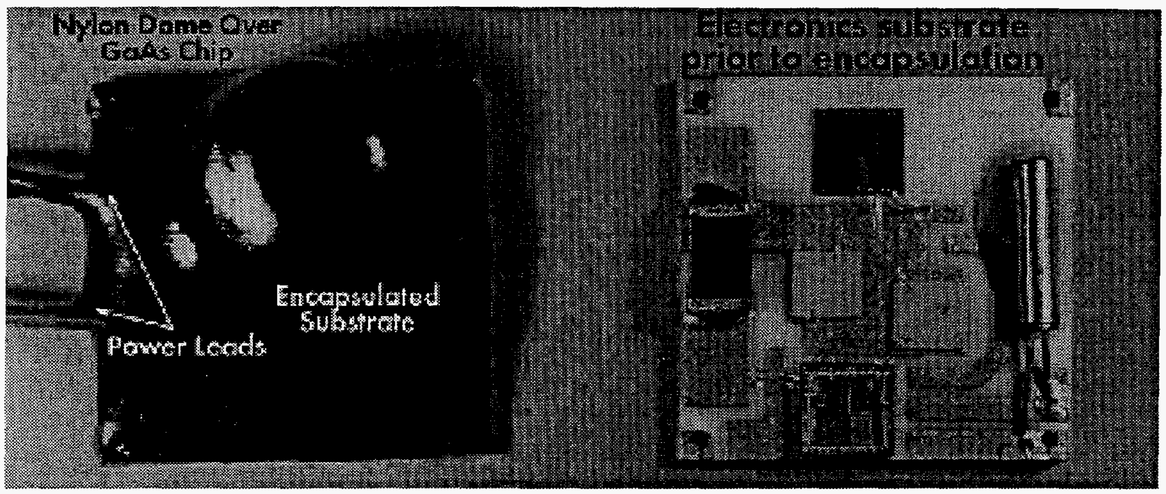


Fig. 4. Pulsed-carrier version of the microtransmitter.

The frequency-shifting capability of the VCO allows the transmitter to generate a frequency-modulated (FM) carrier when modulated by an analog signal from a surveillance sensor. This transmitter has been linked to a standard commercial video camera to implement a prototype wireless camera system for visual surveillance. Audio transmissions could also be implemented in a similar fashion. By applying a digital signal to the VCO control, a frequency-shift-keyed transmitter is implemented. The ability to shift the transmitter frequency over a 1-GHz span provides the capability for digital transmission rates on the order of tens of megabaud. Preliminary laboratory measurements indicate that this transmitter design can be adapted to direct-sequence spread-spectrum transmission, which would provide a low probability of intercept and/or detection of the signal.

7. CONCLUSIONS

A micro-miniature rf transmitter with on-chip antenna has been developed by ORNL. The transmitter chip is applicable to covert law enforcement surveillance and tracking operations because of its extremely small size. Variations of the design have been demonstrated for tracking and tagging beacons and for transmission of real-time analog video and digital data.

8. REFERENCES

1. Falter, D. D. et. al., "Development of a Solar-Powered Infrared Injection Laser Microminiature Transmitting System", *Proceedings of the International Conference on Lasers '89*, New Orleans, Louisiana, December 3-5, 1989.