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A simple miniature device for wireless stimulation of neural circuits in small behaving animals

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ABSTRACT

The use of wireless neural stimulation devices offers significant advantages for neural stimulation experiments in behaving animals. We demonstrate a simple, low-cost and extremely lightweight wireless neural stimulation device which is made from off-the-shelf components. The device has low power consumption and does not require a high-power RF preamplifier. Neural stimulation can be carried out in either a voltage source mode or a current source mode. Using the device, we carry out wireless stimulation in the premotor brain area HVC of a songbird and demonstrate that such stimulation causes rapid perturbations of the acoustic structure of the song.

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1. Introduction

Electrical stimulation of neural circuits is an important tool in neuroscience allowing the studies of the connectivity of neural circuits (Swadlow, 1998), the relation of neural activity to behavior (Wang et al., 2008; Houweling and Brecht, 2008), and the reward mechanisms in the brain (Olds and Fobes, 1981). Electrical stimulation of the brain also has important therapeutic applications (Perlmutter and Mink, 2006; Tarsy et al., 2008). When applied to studies of the effects of neural stimulation on animal behavior, it is important that the chronically implanted stimulating device does not interfere with the animal movement and behavior. Wireless chronic stimulation systems offer a significant advantage in that the animal does not need to be tethered, thus, the behavior is minimally affected by the stimulation device. In addition, wireless stimulation allows carrying out behavioral experiments which are virtually impossible with the stimulation systems requiring a tether, for example, for studies of animal behavior in 3D environments.

Below, we describe a simple and low-cost device for wireless stimulation of neural circuits in behaving animals. The device has a simple schematic, is lightweight and is easy to make from commercially available components.

A number of wireless neural stimulation devices have been described in the literature (Wise et al., 2004; Peng et al., 2004; Pinkwart and Borchers, 1987). Despite recent progress of the wireless stimulation techniques, the task of neural stimulation in small behaving animals (e.g., songbirds, mice) is not easily solved with existing devices. Wireless stimulation devices have to make compromises between the size/weight, the power consumption, the capabilities of the device and the ease of the device fabrication and control (Millard and Shepherd, 2007; Ativanichayaphong et al., 2008). Most lightweight devices that are suitable for chronic studies of small behaving animals are based on custom-made micro-chips (Arfin et al., 2009; Ghovanloo and Najafi, 2007), thus, requiring microfabrication capabilities that are often beyond the means of neuroscience labs. Recent designs of wireless stimulating devices often use a digital mode of communication between the transmitter and the receiver (Ye et al., 2008; Xu et al., 2004). Although sending digital commands to the wireless stimulation device is usually more reliable, digital control of the wireless device complicates the hardware and the software used for the control of the neural stimulation and, additionally, usually increases the power consumption of the device, thus, either reducing the battery life or increasing the weight of the device. There is a need for simple, low-cost and lightweight neural stimulation devices that can be built from off-the-shelf components and controlled using simple and customizable interfaces.

Below, we demonstrate a simple and low-cost device for wireless stimulation of neural circuits in small behaving animals. The device weighs only 1.4 g and is suitable for studies of songbirds that weigh only 12–15 g. The device can be made using readily available components. It can be used either as a voltage source or, with a slight design modification, as a current source. In the voltage source mode, the device has an excellent battery life. Triggering the neural stimulation pulses is carried out by an external command voltage

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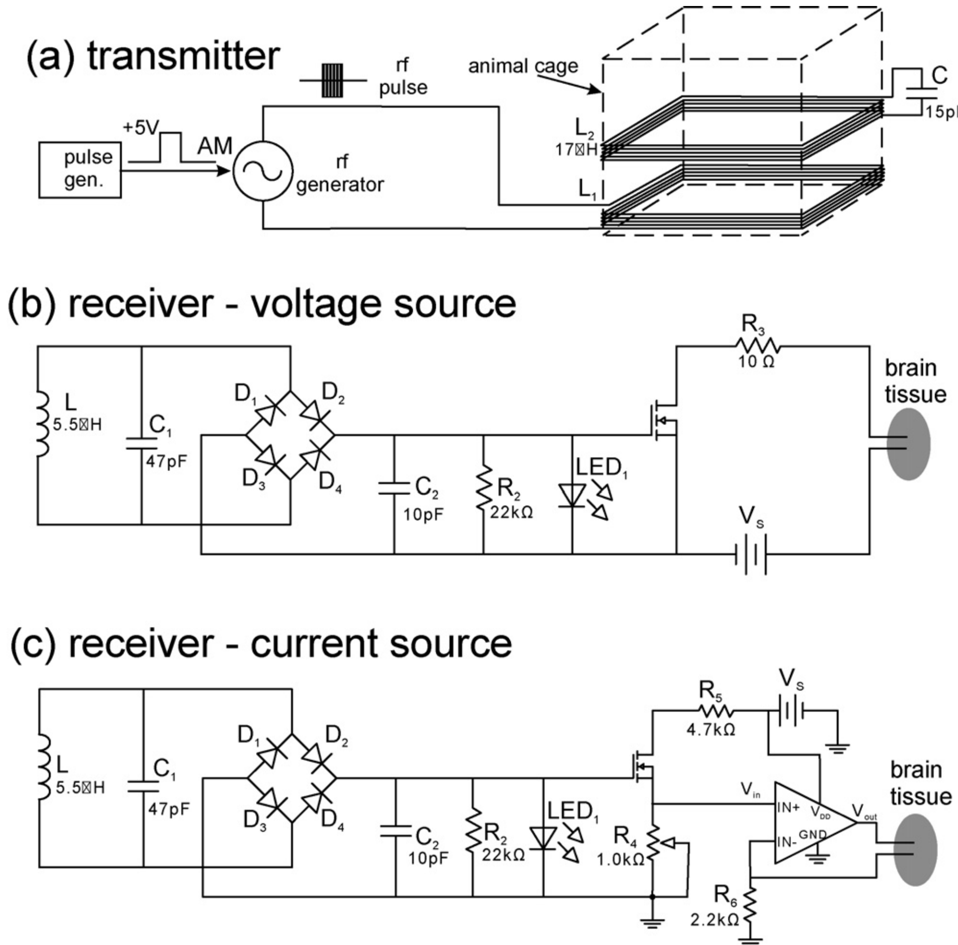

Fig. 1. Schematic of the wireless stimulation system. (a) Transmitter. (b) Schematic of the receiver and voltage source stimulator. (c) Schematic of the receiver and current source stimulator.

pulse (+5 V); thus, it is easy to control the stimulation and to make the system compatible with a variety of software and hardware platforms. The RF voltage required for neural stimulation is quite low (<10 V amplitude), so wireless neural stimulation can be carried out with a commercially available RF source and without a high-power RF amplifier.

2. Methods

2.1. Overview

The wireless stimulation system consists of two parts—an RF transmitter and a light-weight receiver/stimulator that is affixed to the head of the animal (Fig. 1). The transmitter supplies RF current through the primary coil that is wound around the animal cage. The receiver picks up RF signals from the transmitter via a secondary coil and generates voltage or current pulses that stimulate the brain area of interest through a bipolar stimulating electrode.

The coupling between the primary coil (transmitter) and the secondary coil (receiver) is near-field inductive: a magnetic field generated by the current in the primary coil induces the e.m.f. in the secondary coil. The voltage induced in the secondary coil is rectified, and the rectified voltage closes the FET switch, thus enabling the electrical stimulation of the brain area of interest.

The transmitter generates a pulse of RF current when turned on by an external command pulse. The command pulse (+5 V) can be generated by either a pulse generator or by a computer using an A/D card. Thus, the stimulation pulse timing and duration are controlled by simple and intuitive means and can be easily adjusted for a specific task. Below, detailed descriptions of the transmitter and receiver operation are given.

2.2. Transmitter

The block diagram of the transmitter is presented in Fig. 1a. The RF signal is generated by an RF generator (Stanford Research Systems, model DS345); the amplitude modulation (AM) input of the RF generator is connected to the output of the pulse generator (AMPI, model Master-8). The command pulse (+5 V) from the pulse generator triggers the synthesizer to generate an RF pulse with the user-defined voltage amplitude up to 10 V. The output of the synthesizer is connected to a wire-wound coil L_1.

The primary coil system consists of two wire-wound coils L_1 and L_2 that are placed around the animal cage (the cage dimensions are 8 in. × 7.5 in. × 7 in., $L \times W \times H$). Coil L_1 is placed near the bottom of the cage; coil L_2 is placed about 1 in. above L_1. Both coils are made out of 5 windings of 22 gauge insulated copper wire. Coil L_1 is connected to the output of the RF generator. Primary coil L_2 has an inductance of $\sim$17 μH and is connected to a capacitor $C \approx 15$ pF. Thus, L_2 and C form a resonant circuit having a resonant frequency of $f_{\mathrm{res}} = 1/(2\pi\sqrt{L_2 C}) \approx 9.9$ MHz. Coils L_1 and L_2 form an air-gap transformer: the ac current in L_1 induces the ac current in L_2. At the resonant frequency, the high-Q resonant circuit has very low impedance; therefore, the current in L_2 is much larger than the current in L_1. Using this air-gap transformer enhances the coupling from the transmitter to the receiver and enables wireless