LED LIGHTING

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An increasing number of people find themselves developing Electromagnetic HyperSensitivity (EHS), an intolerance to electric and magnetic fields from power line to cell phone frequencies. Like food intolerances to peanuts, wheat, etc., avoidance is the primary mechanism to maintain some minimal level of health. The first thought of those with EHS is to move to some remote mountain valley with low electromagnetic fields (EMFs), but this is not always feasible because of job or family obligations.

I have been looking at the possibility of building houses with low inside EMFs which would allow the afflicted to get a good night's rest and improve their quality of life. One concept is to build the four outside walls of the house with concrete that absorbs EMFs. The roof and siding would be metal sheets that reflect EMFs. The house would need to be off grid to reduce the power line EMFs. Electrical power would be provided by photovoltaic panels and deep discharge batteries. I think that a 24 VDC system is a reasonable choice. The house may need to have a 24 VDC to 120 VAC inverter to power some appliances that are not easily converted to 24 VDC operation, but operation of an inverter should be limited because of the EMFs it produces, and the general loss of efficiency.

Therefore it is desirable to have lighting that works directly from 24 VDC batteries, and is as efficient as possible. The obvious choice is Light Emitting Diodes (LEDs), which has swept the market for flashlights. These are packaged in many configurations, one of which is in a five meter long strip with typically 300 LEDs on it. One can get on Ebay, type in "12 V warm white LED" and get thousands of hits. Two common versions are the 3528, where the individual LED chips are 3.5 mm by 2.8 mm, and the 5050, with chips 5.0 mm by 5.0 mm. My only experience is with the 3528 warm white version.

These strips are about 8 mm wide, with an adhesive backing so they can be placed directly on the ceiling without the need for an electrical box or luminaire. Parallel strips extending from one wall to the other produce very uniform lighting at all points in the room, much more uniform than produced by one bulb in the center of the ceiling. The advantages of no fluctuations at power line frequency, uniform light distribution, and higher efficiency suggest that this lighting concept will rapidly take over the lighting market.

I installed LED strips in an old off-grid camper in 2012. The nominal battery voltage is 24 VDC, however the actual voltage might be as high as 28 VDC while the batteries are being charged in full sunlight. Two 12 VDC LED strips were connected in series to get the applied voltage somewhat close to the rated voltage. I found the resultant lighting to be pleasant and of adequate brightness. But the small camper size and narrow aisle made it difficult to collect meaningful data that would be applicable to normal household sized rooms.

I bought a three bedroom, two bath, 1500 square feet house in Rockvale, Colorado in May, 2014 and installed LED strips on the ceiling of one of the bedrooms (size 11 ft 5 inches by

11 ft 11 inches) for test purposes. I assumed that there would be dozens of Youtube videos and other sources on the Internet that would discuss the design process, and answer questions like: How many LEDs are needed per square foot of ceiling to get a specific light level? These sources may be there, but I was not able to find them. So the number of LEDs I installed per unit area were just a guess. Fortunately, it turned out to be a good guess.

I bought eight of the 5 m (197 inches) strips for the bedroom at \$7.84 each, or a total of \$62.72 postpaid from China. I cut about 1/3 off each strip (actually a piece 66 inches long with 102 chips) and soldered two of the cut ends together so I had 8 strips about $197 - 66 = 131$ inches with 198 chips and 4 strips about $2(66) = 132$ inches long with 204 chips. These were then installed with equal spacing (about 11 inches) across the ceiling. The strips start about 2 inches from one wall and end about 4 inches from the other wall. The room has one outside window. Three walls are painted in a semi-gloss white, and the fourth mostly in black. Illumination levels would be slightly higher if all walls were painted in white (better reflection). I put four strips on one switch and eight strips on another switch so we could have different light levels. The expectation was that four strips should be plenty for dressing or surfing the Internet, while reading a book might require eight or twelve strips. This capability of drawing just enough battery power to meet the application need is important in an off-grid situation.

The circuit diagram is shown in Fig. 1. M_1 and M_2 are low voltage, low resistance power MOSFETs used for switching. Two of the 12 VDC strips are connected in series to get a nominal 24 VDC rating, such as strip 1 and strip 2. The series combination of strip 3 and strip 4 is then connected in parallel with strips 1 and 2, such that all four strips are turned on when M_1 is switched on. Similarly, strips 5-12 are turned on by M_2.

In a typical off-grid setting, the battery would be four 6 V deep-discharge types connected in series, charged by PV panels. The measured voltage would vary according to the available sunlight, the state of charge, and the voltage drop in the wires between the batteries and the LEDs. The illuminance level will vary proportionally with the voltage. Any attempt to make the illuminance level constant with variable input voltage will result in greater losses and possibly greater EMFs. My guess is that a variable illuminance level will be barely noticeable and not a problem, so I made no attempt to stabilize the level.

The batteries, battery vault, PV panels, circuit breaker, and wiring would cost upwards of \$2000. The LED strips were installed on one bedroom of an all-electric home just for test purposes. System components besides the LED strips were being tested elsewhere, so there seemed little point in going to the expense and effort (including boring a hole through a concrete wall of the house) and actually installing a full battery system. Instead I bought a 10 A Allen-Bradley power supply, 120 VAC input and adjustable 24-28 VDC output.

The series-parallel construction also occurs on each LED strip. A given LED strip has three copper traces. The outside traces are continuous, one for +12 V and one for 0 V. The inner trace connects between adjacent LED chips. Starting at the input end of the strip, the first three LED chips will be connected in series between the +12 V trace and the 0 V trace.

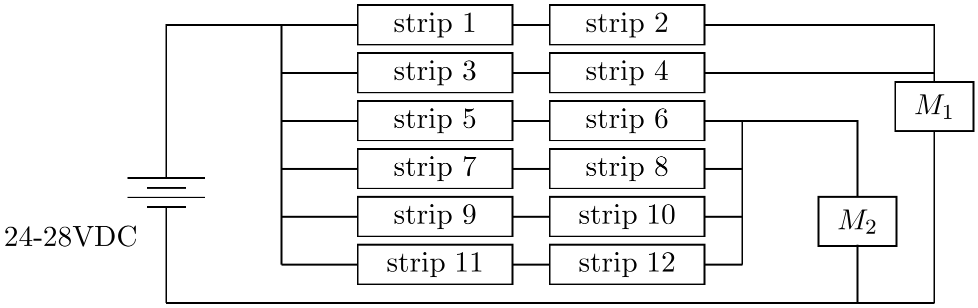

Figure 1: LED circuit diagram.

The next three chips will be connected in parallel with the first three and so on down the strip. In a strip 5 m long with 300 chips, there will be 100 groups of 3 chips each connected in parallel.

I used ordinary light switches in the camper, rather than MOSFETs. This 'quick and dirty' technique works, but is definitely not 'best engineering practice' for at least two reasons. One reason is that the MOSFETs allow a higher efficiency. In normal 120 VAC wiring, the light switch carries the full current of the lights. The wire carrying the current from the breaker box may pass over the light fixture, continue on to the door opening, down the wall to the switch location, and then back up and over to the fixture. If the switch were located right at the fixture, the copper losses and voltage drop in the wire between the fixture and the wall switch would be eliminated. These losses are a much greater percentage of the total load power in a 24 V system as compared with a 120 V system.

It is customary to justify increased expense to improve efficiency by calculating a simple payback period. That is, how long does it take for the savings from greater efficiency to pay back the extra cost? Every case has its own set of parameters. I will assume some plausible numbers to illustrate the process for this case. The feed point of the LEDs is at ceiling level in one corner of this bedroom, diagonally across the room from the door and the proper place for a switch. The total length of wire is about 20 feet. This is two conductor wire, so two conductors over to the switch and back to the feed point is a total of 80 feet of single conductor. I assume 12 gauge copper wire, which has a resistance of 1.588 ohms per 1000 ft at 20^oC. The circuit involving 8 strips draws 6.35 A at 28 VDC. The power dissipation is then

$$P = I^2R = (6.35)^2(80/1000)(1.588) = 5.12 \ \ W \tag{1}$$

Assume 3 hours of operation per day, 365 days per year. The yearly energy usage is (3)(365)(5.12) = 5.61 kWh/year. Assume \$0.15 as the cost of one kWh. The yearly cost of 5.61 kWh is \$0.84. The MOSFET used in this test costs \$1.29 each from Digikey in quantities of 25. The simple payback period is 1.29/0.84 = 1.53 years for just the MOSFET. The life of the MOSFET is at least 20 years and probably far longer. Most investors are more than happy to buy things with a 20 year life that pay for themselves in a year and half.

A second reason for using a MOSFET is more subtle, but may be even more important than the efficiency improvement. Light switches available at the local hardware store are not UL rated for switching direct currents. Switching a current off always produces a small arc between the opening contacts. A 60 Hz alternating current goes through zero 120 times per second, which always eliminates the arc in a properly functioning switch. A direct current has no zero crossing, so the arc tends to last longer, which degrades the contacts. A switch turning off 5 A DC will fail sooner than one turning off 5 A AC. And it is not impossible that the failure mode will involve a continuous arc, which would be a definite fire hazard. Using devices that are not rated for the application is a *bad* idea. The electrical inspector might not stop you, but the fire hazard should.

A mechanical switch is still required, to turn on a MOSFET by applying a voltage to the MOSFET gate. The switching circuit diagram is shown in Fig. 2. The mechanical switch in Fig. 2 also switches DC, but slightly less than 1 mA rather than the several amps required by the LEDs. (The gate of the power MOSFET is essentially a high quality capacitor that draws almost no current once charged so all the current flows through the 10K and 20K resistors.) This tiny current is enough to 'wet' the switch contacts, but far below the amplitude necessary to sustain an arc or cause a fire. A standard hardware store AC switch should last significantly longer while switching 1 mA DC than while switching several amps AC.

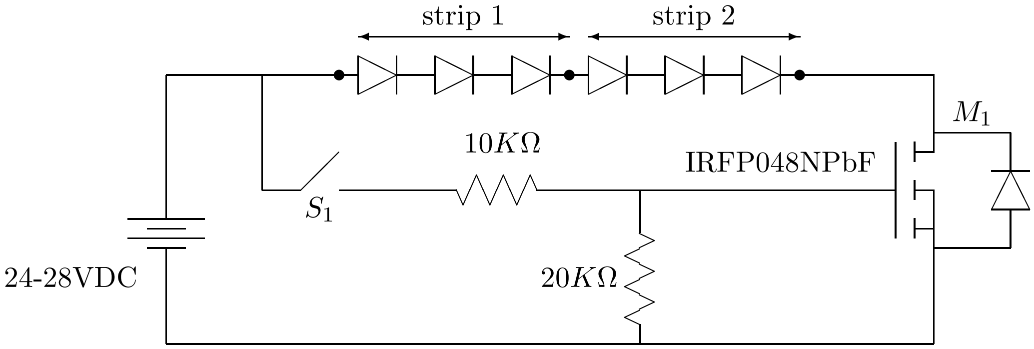

Figure 2: LED switching circuit.

Three of the individual LED chips in strip 1 are shown in Fig. 2, as well as three chips in strip 2. Electrically, every chip on strips 1-4 are a part of a group of six chips connected in series across the 24-28 VDC supply. Other groups of six chips are connected in parallel across the first group to complete the circuit, and likewise for strips 5-12 controlled by M_2.

The gate voltage of this MOSFET is limited to 20 V, which requires the 10K and 20K resistor combination to reduce the 24-28 VDC battery voltage to less than 20 V.

The power MOSFET needs to have an 'ON' resistance as low as possible to maintain high efficiency in the circuit. The IRFP048NPbF will withstand 55 V while 'OFF' and is rated at 64 A while 'ON'. The nominal resistance is 0.016Ω. The MOSFET driving the 8 strips at the maximum voltage of 28 VDC had a measured current of 6.35 A and a measured voltage drop of 68 mV, or an effective resistance of $0.068/6.35 = 0.0107\Omega$. The power loss in the MOSFET was $(0.068)(6.35) = 0.43$ W, which is about a quarter of one percent of the $(28)(6.35) = 177.8$ W supplied to the LEDs, or a negligible value.

I will now present some numerical results. These should not be considered the final word on anything. I have no way of knowing if the LED strips I purchased are top-of-the-line or bottom-of-the-line. I suspect that the lumens per LED chip can vary significantly from one manufacturer to the next, and likewise the lumens per watt. I compared the LED strips I happened to buy on Ebay with one incandescent bulb (100 W) and one 23 W CFL ('equivalent to a 100 W incandescent') at one power line voltage. Your mileage may vary.

Two terms need to be defined. The *lumen* (lm) is the "total" light radiated by the bulb. It may be called the luminous flux or the luminous power. The *illuminance* is the light incident on a surface, in lm/m^2 or lux. It is recommended that a family living room have at least 50 lux. Hallways and toilets in an office building should have 80 lux. Working areas in an office building should have 320 to 500 lux.

The test room had a ceiling fan with a socket for a single bulb below the fan. The filament within an incandescent bulb would be about 11 inches below the ceiling. The LED strips were, of course, mounted directly on the ceiling. The illuminance of a point source decreases as the square of the distance, so the illuminance at table height will favor the light bulb over the LEDs because the light bulb is closer to the table, at least through the central part of the room. There is additional bias in favor of the light bulb because the light from some LEDs is blocked by the fan blades, but the bulb is well below the blades. To eliminate as much of that sort of bias as possible, I measured the illuminance at a distance one foot from the floor. I measured the illuminance at ten points a foot apart through the center of the room, and another ten points along one bare, white wall. The voltage to the LEDs was set at 26.7 VDC. The mean and the standard deviation of the 20 data points are given in the following table, for the cases of 4, 8, and 12 strips active, a 100 W incandescent bulb, and a 23 W CFL bulb.

	4 strips	8 strips	12 strips	100 W	23 W
Mean	125.6	249.5	371.1	70.4	70.4
S.D.	26.2	37.8	57.2	20.6	18.4
S.D./Mean	0.209	0.151	0.154	0.293	0.261
Power	79.3	149.4	219	103.5	22.3
Lux/Watt	1.584	1.67	1.695	0.68	3.088

The CFL bulb was made by ACE Hardware, soft white, 2700K, \$12.85 for five bulbs in early November 2014. The test bulb was new out of the box and seasoned for four hours before testing. I would expect the illuminance to slowly decrease over the life of the CFL, so this is the most favorable time to measure the bulb. The 100 W incandescent was also made by ACE Hardware.

It just happened that the mean illuminance of the incandescent and the fluorescent bulb were exactly the same at 70.4 lux. The claim that a 23 W CFL is equivalent to a 100 W incandescent is supported by this test.

The LED strips produce a more uniform illuminance. The ratio of standard deviation to mean would be a measure of variability. The ratio for the 12 strip case was 0.154 while the ratio for the incandescent bulb was 0.293, almost double. The highest and lowest illuminance values for the 12 strip LED case were 450 and 259 lux, a ratio of 450/259 = 1.74. The highest and lowest values for the incandescent bulb were 105 and 36 lux, a ratio of 105/36 = 2.92. I personally much prefer this more uniform illuminance.

The single 100 W bulb gets the illuminance up into the proper range for a living room, enough to watch TV by, but not quite enough for many activities. The 4 LED strip case has almost twice the illuminance of the single 100 W bulb, and the 12 LED case is quite adequate for office work. I personally like all three illuminance levels, but if the power and energy budget for an off grid house just did not allow for these power levels, I could easily get by with 2 LED strips (instead of 4) for the first level, and 8 LED strips (instead of 12) for the highest level.

The light output of any LED is proportional to the current through the LED, so I checked the illuminance of the 12 strip case as the applied voltage varied from 24 to 28 VDC. Results are given in the following table.

VDC	P	lux	lux/P	lux/2.04P
24.05	142	289	2.04	1.00
24.57	157	307	1.96	.961
25.04	171	322	1.88	.922
25.48	185	337	1.82	.892
25.97	199	352	1.77	.868
26.47	216	369	1.71	.838
26.96	233	382	1.64	.804
27.52	254	398	1.57	.770
27.99	272	411	1.51	.740

We see the input power to the LED strips increase from 142 to 272 W as the applied voltage increased from 24.05 to 27.99 VDC. The illuminance increased from 289 to 411 lux, the mean of 20 points in the room measured one foot above the floor. The illuminance per watt decreased from 2.04 to 1.51 lux/watt, and the normalized illuminance per watt decreased from 1.00 to 0.74. The illuminance increases as the current and the losses increase as the square of the current, so this decrease in efficiency with increasing voltage is expected.

It is always interesting to compare the efficiency of the different light sources. It seems fair to do the comparison at rated voltage for each type of light source (12/24 VDC for LED strips, 120 VAC for incandescent and CFL). The LEDs produced 2.04 lux/watt at approximately 24

VDC while the 100 W incandescent bulb produced 0.68 lux/watt at approximately 120 VAC, a ratio of 3.0. That is, these particular LED strips are 3 times as efficient as a 100 W incandescent bulb, in addition to a more uniform illuminance, a longer life, and a simpler connection to a 24 VDC off grid system. The LED strips are an obvious winner in any choice between LEDs and incandescents.

But there is a third option, the CFL. The CFL tested was $3.088/0.68 = 4.54$ times as efficient as the incandescent bulb, significantly better than the LED strips. This was a surprise to me as I had expected the LEDs to be at least as efficient as the CFL. The sellers of LED strips on Ebay are typically vague about the lumen rating of their strips, but I found one supplier who stated "Each 3528 emits approximately 7 lumens/chip". I had installed $(8)(300) = 2400$ chips on the ceiling of the test room, or a nominal $(2400)(7) = 16,800$ lumens if I had purchased that particular LED strip. A typical 100 W incandescent bulb claims a 1690 lumen output. At 7 lumens per chip, I should have had about 10 times as many lumens being emitted from the ceiling of the test room as from the single 100 W bulb. The illuminance is, of course, directly proportional to the number of lumens emitted. A small correction factor needs to be applied when we are comparing a distributed source (LEDs) and a concentrated source (100 W bulb), but I would still expect the mean illuminance near the floor to be about ten times as great for the LED strips as for the 100 W bulb, both operated at rated conditions, if the LED chips are indeed emitting 7 lumens per chip. Instead, I measured a ratio of $(289/70.4 = 4.11)$. My first guess as to the cause of this discrepancy is that the 'bargain' LED strips I bought were not as much of a bargain as I thought. I will definitely ask the seller about the lumens per chip for the next batch of LED strips that I buy on Ebay! My guess is that with just a little diligence in purchasing LEDs of reasonable quality, the LED efficiency will be as good as, or even better than the CFL efficiency. Certainly, we do not want to reject the use of LEDs as compared with CFLs, based on this one sample.

Another reason to select LEDs over CFLs (for those of us with EHS) is that CFLs add electrical noise to the electrical wiring in a house. There is a meter available, called a Stetzer meter, that plugs into an electrical outlet and gives a reading proportional to the electrical noise, or *dirty electricity* on the outlet. The reading is in arbitrary Stetzer units. If the reading is above some value like 50 units, the person with EHS is encouraged to buy Stetzer filters, which plug into wall outlets and absorb a portion of the dirty electricity. The house where this testing is occuring is at the very end of a single-phase distribution line, with a mountain on one side and low density housing (lots one acre or more) on the other side. High frequency signals (dirty electricity) tend to attenuate fairly rapidly with distance from the source, so the relatively large distances from neighbors suggest that the Stetzer readings might be low. Indeed that has been my experience in this house. I have checked the Stetzer readings regularly over the past several months, and most of the time have seen numbers between 10 and 30. The readings vary with time of day, loads within the house, weather, and presumably what the neighbors are doing, but almost always below 50.

I plugged the Stetzer meter into an outlet on the same circuit as the CFL, and watched the readings for an hour or so, while different loads were switching on and off in the house (refrigerator, incandescent lights, etc.). Readings were briefly in the range of 30 to 50, mostly between 100 and 150, and as high as 400. One CFL *really* increases the level of dirty electricity! When I moved into my present house in Canon City (about 7 miles away from the test house in Rockvale), I took out all the CFLs and replaced them with incandescent bulbs, and recommend that the readers of this article do likewise. Even if CFLs were always slightly more efficient than LEDs, I would still recommend using LEDs because LEDs do not add electrical noise to the wiring.

Getting power to each LED strip raises some interesting questions. When wiring for a ceiling light using incandescent bulbs, it is not difficult to hide the wires behind the studs and drywall. Only the switch and light fixture are visible in the room, giving a neat and tidy appearance for the wiring. In my test house there were 12 LED strips on the ceiling, ending about 2 inches from the wall. Each strip needed to be connected to 12 gauge wires carrying a nominal 24 VDC. The cheapest and quickest method to do this was to keep the wires inside the room, along the corner between wall and ceiling, rather than trying to hide the wires behind the existing drywall. This would still be a preferred method even in new construction. This means that a *raceway* needs to be built along this corner, to support the 12 gauge wires. The raceway needs the capability of being closed after the LED strips are installed, to improve the 'neat and tidy' appearance. The electrical inspector will probably not be overly concerned with appearance, but will want to see that the wires are protected from mechanical injury.

We have been using surface mounted wiring (raceways, wire molding) ever since we started adding electricity to old houses a century ago, so there are many components available on the market. Unfortunately I could not locate raceway that was 'just right' for this application. Typically, there is a channel with one open side that is installed along the wall or ceiling between switch and fixture. Wires are placed in the channel and then a cover is installed to totally inclose the wires. In my case, the wires from the raceway to each LED strip would be mashed by the cover. Either the wiring would be damaged or the cover just would not go on. We need a raceway with a cover that has a gap along one side to allow space for the LED wiring.

If the LED strip lighting catches on the way I think it will, the raceway manufacturers will eventually market something that is 'just right'. In the meantime, I built my own raceway with aluminum piano hinges 6 ft long and 1 and 5/8 inch wide, available from McMaster-Carr. One side of the hinge is mounted horizontally on the wall about two inches below the ceiling with brackets that do not interfere with the wiring. The other side of the hinge hangs straight down while wiring is being done, and then is swung around to the straight up position to mostly inclose the wiring. The wires from the LED strips pass through the 3/8 inch gap between the hinge and the ceiling. The bottom of the raceway can be drilled to allow metal (or plastic) conduit to go down the wall to switch or outlet boxes.

I believe the result provides adequate mechanical protection for the wiring to pass electrical inspection. It is certainly not as attractive as hidden wiring, but in my opinion looks reasonably neat and tidy.