

Laser Guitar

by

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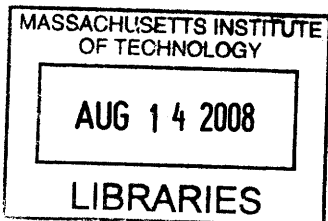
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Abstract

Music is constantly evolving, both in the culture and musical theory that dictates its structure, and the technology used to create the actual sound. This thesis explores a direction for development of one of the most proven instruments in musical brainstorming as well as live performance; the guitar. The form and feel has stayed nearly the same since its conception and it is a solid foundation with which to integrate modern technology. The design is to replace the strings with beams of laser that run through a line of beam splitters at each fret, each of which sends a beam onto a photoresistor. By blocking the beam at different frets, the current through the resistors uniquely determines what fret is pressed. The motivation for this development is twofold; firstly, the aesthetic appeal of a brilliantly lit guitar could make this a popular instrument for live shows, and, secondly, the lasers would be more versatile than strings, allowing the player to program frets to be any note. By doing this, the writing process could be enhanced with more options to experiment with, and the performance of difficult compositions could be simplified. This paper begins the design of the instrument and proposes solutions for some possible complications in creating it.

Thesis Supervisor: David Wallace

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Introduction

Music is a balance of artistic, conceptual ideas and the skill of using technology to physically create the sound. Both are constantly evolving; ideas change as taste and culture demand, and, of course, technology is always progressing, providing more options for musicians.

Guitars are one of the most popular instruments, for both brainstorming ideas and performance of live music. They are brilliantly set up to be convenient for chords and melodies, making them easy to learn and play. The form and feel of guitars has remained mostly unchanged, aside from the introduction of electricity. Even so, there have been many minor improvements to guitars; designs for the body have been altered for better sound, locking systems are used to maintain tuning, or capos for changing keys to name a few.

Although many parts of a guitar contribute to the resulting sound, the most important component is the strings. While the other sections of the guitar may alter the quality of the sound, the strings alone are responsible for changing pitches, the building block for the music theory mankind has spent centuries developing. They are directly manipulated by the guitarist using the concept that the longer and thicker a string is, the lower the frequency of vibration will be. The general technique for playing is to use one hand to shorten the string to the desired pitches' length by pressing the string to the fret board, while the other hand plucks the string to produce the actual vibrations needed for a sound. If the string is not pressed, it is referred to as an "open string".

It should be noted that many alternative techniques have developed over the years (tapping, sliding, pull-offs, etc.), but the above mentioned "standard" style of play is the only method that will be focused on in this design.

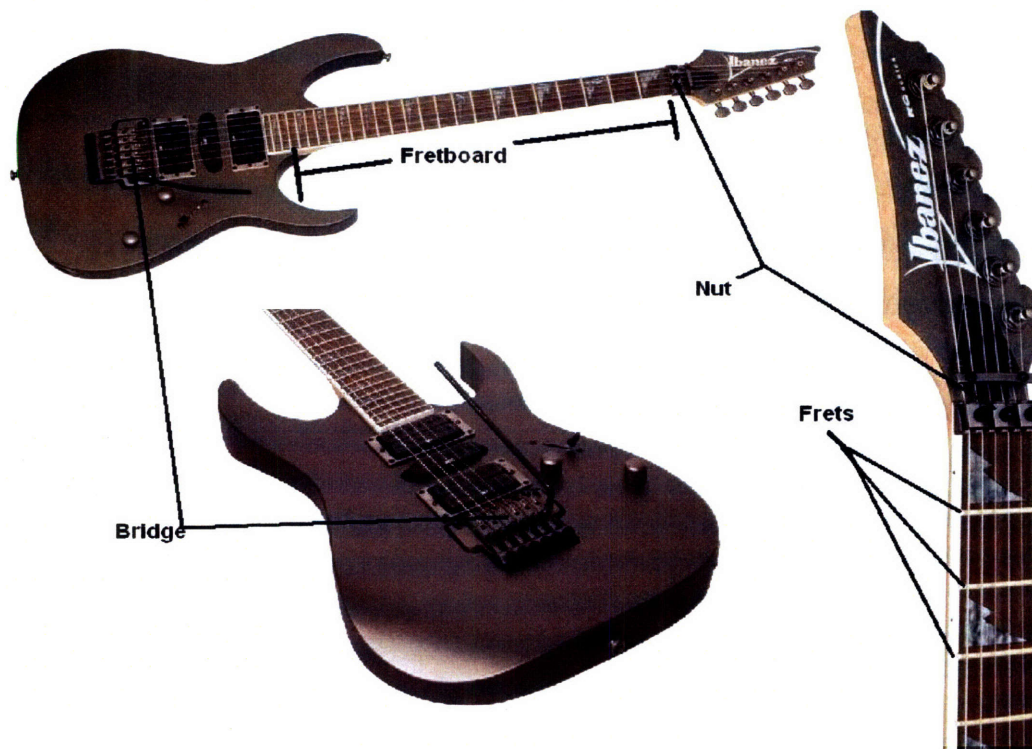


Figure 1 – Layout of a typical guitar. The fret board is the entire span of the neck containing 20 -24 frets. The bridge is on the body of the guitar; the nut is on the opposite end where the strings leave the fret board. (Photo of an Ibanez RG5EX1 electric guitar [2])

Strings come in a variety of material (usually nickel, steel, or nylon [2]) and different forms (either a simple wire or coil around the axis of a normal wire). Different gauge strings are used as well; for example the heaviest string can range from .038 inches (useful for quick playing and less resistance) to .054 (useful for heavier strumming, more pure tone, and low tunings). The differences are subtle to an unobservant novice, but enthusiasts typically have strong preferences, even several preferences for different styles of music. While the improvements over the years are somewhat minor, it's unfair to say that the technological progress behind strings is stagnant; even today there are developments. For example, Elixer, a popular guitar accessories manufacturer, has developed Polyweb and Nanoweb strings with a thin coating on the string to increase string life, improve sound, and reduce “squeaking” of fingers sliding [3]. Many other changes have been made, all slightly altering the sound, life, and feel. Strings are the part of the guitar the musician is most intimate with, and accordingly get attention to fine details.

This project will describe an idea for substitution of the strings with another medium - light.

Concept

This concept uses lasers and photoresistors to detect the player's intentions, sending a signal to a computer to play the actual sounds. This is a radical change, but there are two main reasons for the idea. The first, though more artistic than utilitarian, is the aesthetic appeal of such an instrument. If developed to a point of manufacturability, it could be somewhat marketable as both a toy and a stylish addition to musicians' live show armament. It could also provide an entertaining project for young kids as a kit to be put together, providing an introduction to some basic concepts of optics and electrical engineering. The second reason is extending options for composition and playability, while maintaining the proven musical set-up of a guitar. For example, since the laser sends a signal of the note being played rather than actually produce a sound, one could experiment with alternative tunings by simply programming the frets to produce different notes. Interesting directions for that could be having an "inverse guitar" with longer strings playing higher notes or only having the notes in a particular scale playable. This ability would enhance the creative process and also make otherwise difficult compositions easier to perform. While I doubt the finished product could compete with the rugged, hands-on experience of a stringed guitar as a staple of musical instruments, it could offer a unique, more modern feel.

The initial conception of the design is divided into two modules, mirroring the two main tasks a guitarist must perform on a string to produce music. By reading the outputs from the modules, a computer could play the desired note.

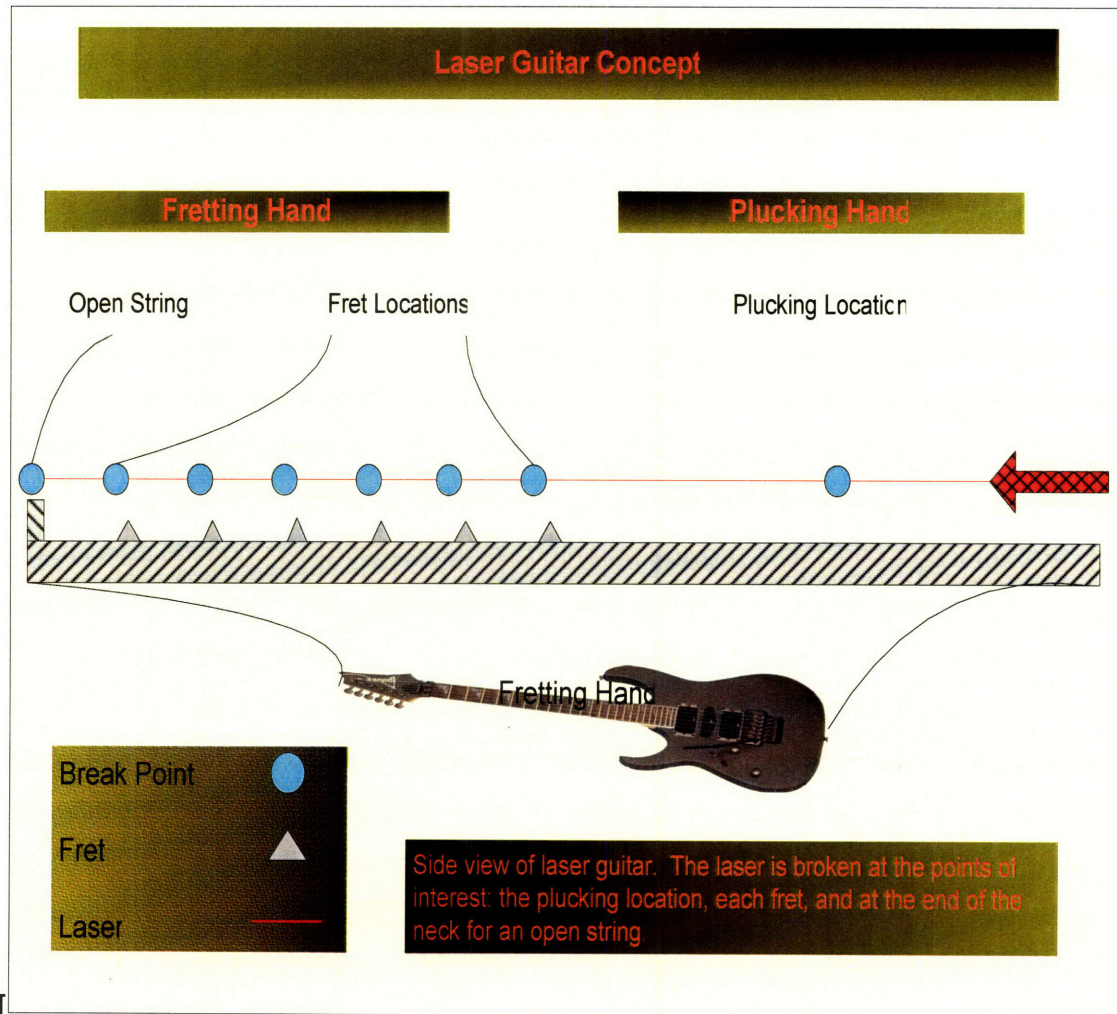


Figure 2 - Conceptual Schematic of the Laser Guitar. The laser spans across the guitar and is broken at points of interest.

The first module represents the right hand (plucking hand). When the right hand plucks a guitar string, the string vibrates, creating audible pitches. Likewise the right hand portion of the laser guitar should be able to determine when a laser has been plucked, briefly breaking the beam, so that a signal can be sent. This is a very binary situation, only needing two states to determine the player's intention.

The second module represents the left hand (fretting hand). When a guitar player strikes a note, his left hand is holding the string down at a unique location. This presents a more complicated scenario for design, because it's no longer an on/off situation. The system needs to be able to tell where the player is touching the fret board at all times, so that when the laser is plucked, the appropriate note can be produced.

One interesting characteristic of a guitar is that the frets allow only certain pitches to be played; they are conveniently the notes in the twelve note chromatic scale. A normal guitar has 20 – 24 frets, allowing a string to play only that many notes (along with the open string note), rather than all the notes in the spectrum between the lowest and highest notes. In contrast, other stringed instruments, such as a violin, have no frets, so the string can be held down at any point, producing any note. Therefore, the laser guitar needs to be able to determine between several states, one for each fret, rather than a continuum.

The first way to conceptualize the idea is separate lasers beams for each the left and right hand sections, but a more compact version is possible. By adding one state to the fretting hand module, there can exist a system with states for each fret and a state to signal a pluck. This will be done by having a beam travel across the entire guitar. The data needed is where the beam is being broken. If the beam is broken in the picking hand side of the guitar and note is intended, while if it is broken at a particular fret, that note should be ready to play the instant a pick is detected.

The design will be based on these concepts: the laser should be broken at different points along the beam, signifying a finite number of responses the guitar player intends.

All States and Responses of System	
State Number	Response
0	Open String
1	First Fret
2	Second Fret
...	...
n-1	N-1 Fret
N	N th Fret
N+1	Pluck String

Table 1 – List of all states for a guitar. With n frets there will be n+2 states.

Design

In order to measure where the beam is split, the design will use a beam splitter at each point of interest with a photoresistor detecting if the beam has been cut off at that point. The photoresistors are connected in series, giving the total resistance a unique value at each point the laser can be blocked.

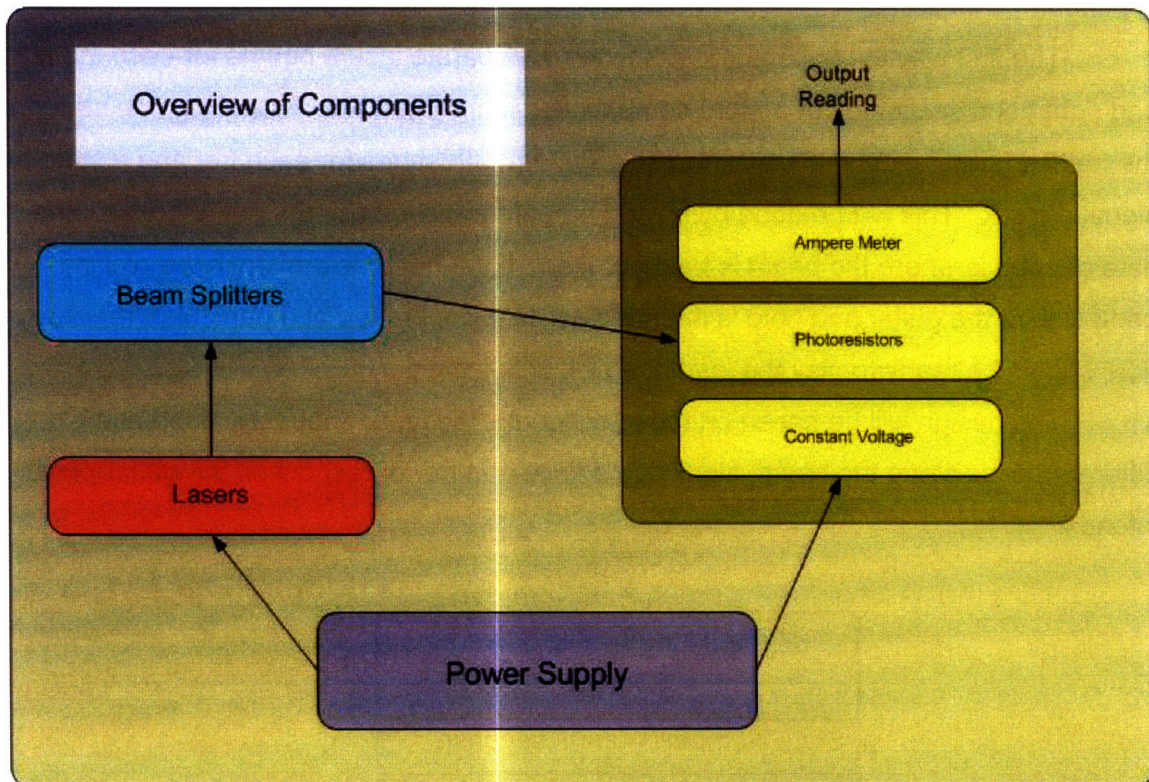


Figure 3 – Overview of Components. Power is needed for the lasers and circuit voltage. The lasers strike the photoresistors, and the circuit outputs varying current readings.

Lasers

For each string a laser is pointed down the guitar from the bridge to the nut. The beam should be just above the fret board so that the beam splitters don't need to protrude out too much. At each beam splitter the laser will be divided into two beams, so the energy in the wave needs to be strong enough to excite the photoresistors at the end of the chain.

Beam Splitter

A beam splitter allows half the incident beam to continue forward while half is directed to the side. At each point of interest, a beam splitter sends a beam to a photoresistor while allowing the laser to continue through.

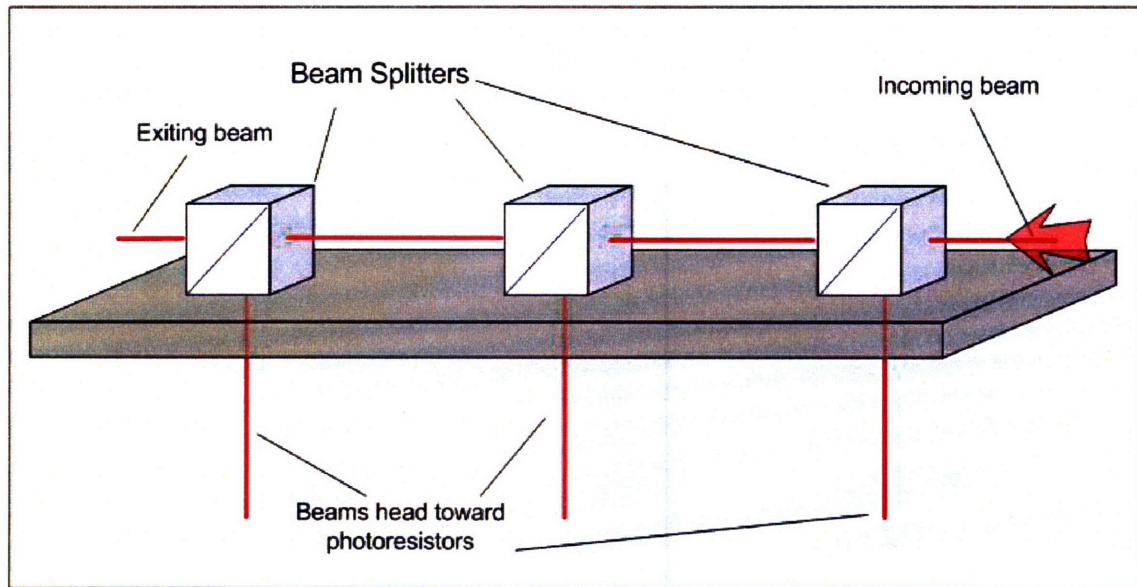


Figure 4 – Beam splitters send one beam to the photoresistor and the other to the next beam splitter.

Resistors

Photoresistors offer a cheap method of measuring whether or not light is present. The resistance of the component decreases exponentially as more light is passed through (see appendix). They are generally most sensitive in the 500-600 nm wavelength range of light, which is convenient for the aesthetic aspect of the guitar, since this is a visible green light. The rise time (from darkness to 1000 lx) is generally 10-20 ms, while the fall time is about 50 ms [4]. In order to limit ambient light from altering the readings, they should be in a hole under the beam splitter.

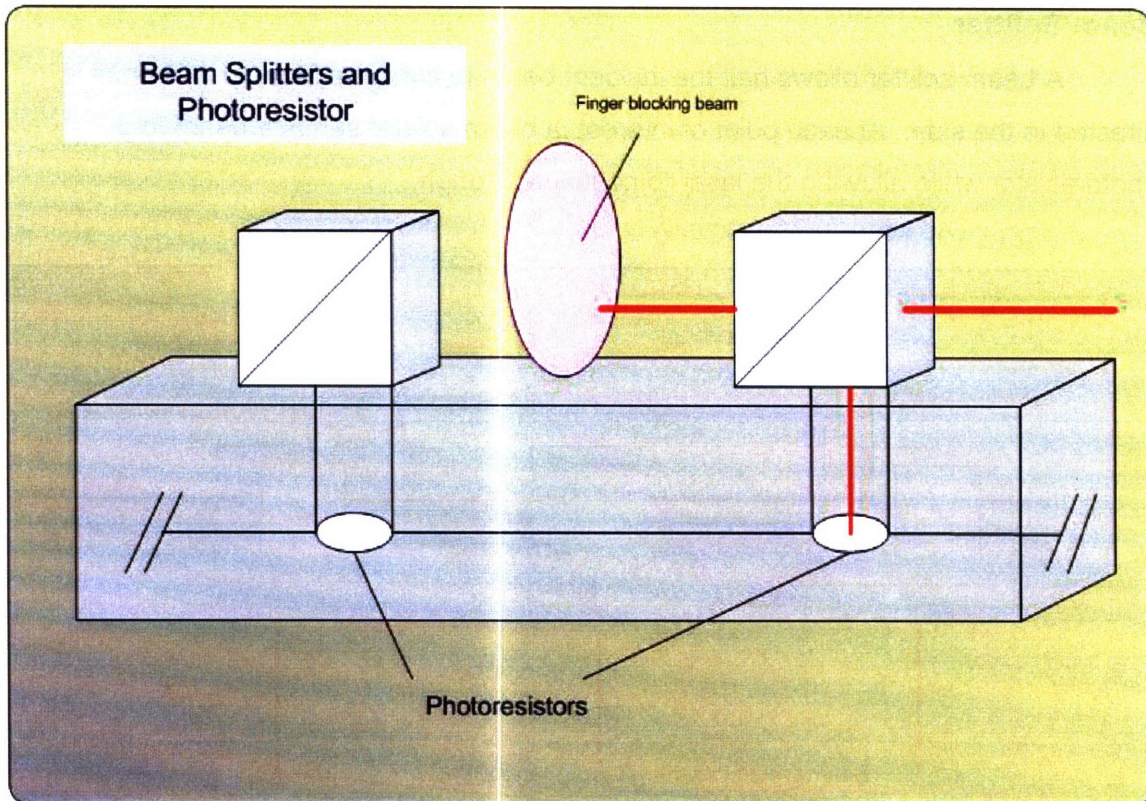


Figure 5 – Example of the beam splitter relaying one beam to the resistor while the main beam continues forward until blocked.

The exponential relationship between the resistance and incident light is useful in that the resistance in light can be approximated as equal for all resistors, since the resistance doesn't change much at very high luminance (See Appendix I for further explanation of the relation between resistance and illumination). At a deeper level of analysis, the later photoresistors would be modeled as receiving less light.

Analysis

The laser can be blocked at any fret. The resistance of each photoresistor, R_i , is

$$R_i = \begin{cases} R_L \\ R_D \end{cases}$$

where R_L is the resistance in light, and R_D , is the resistance in dark. The light's intensity decreases at each beam splitter, so the further resistors receive less, but the exponential relationship between resistance and luminous flux means that the resistance doesn't

decrease much after a reasonable amount of light is incident. Therefore all the resistors can be assumed to have the same R_L and R_D .

With the resistors in series, a constant voltage supply can be applied to the circuit. As the photoresistors change, the state of the system can be read by measuring the current.

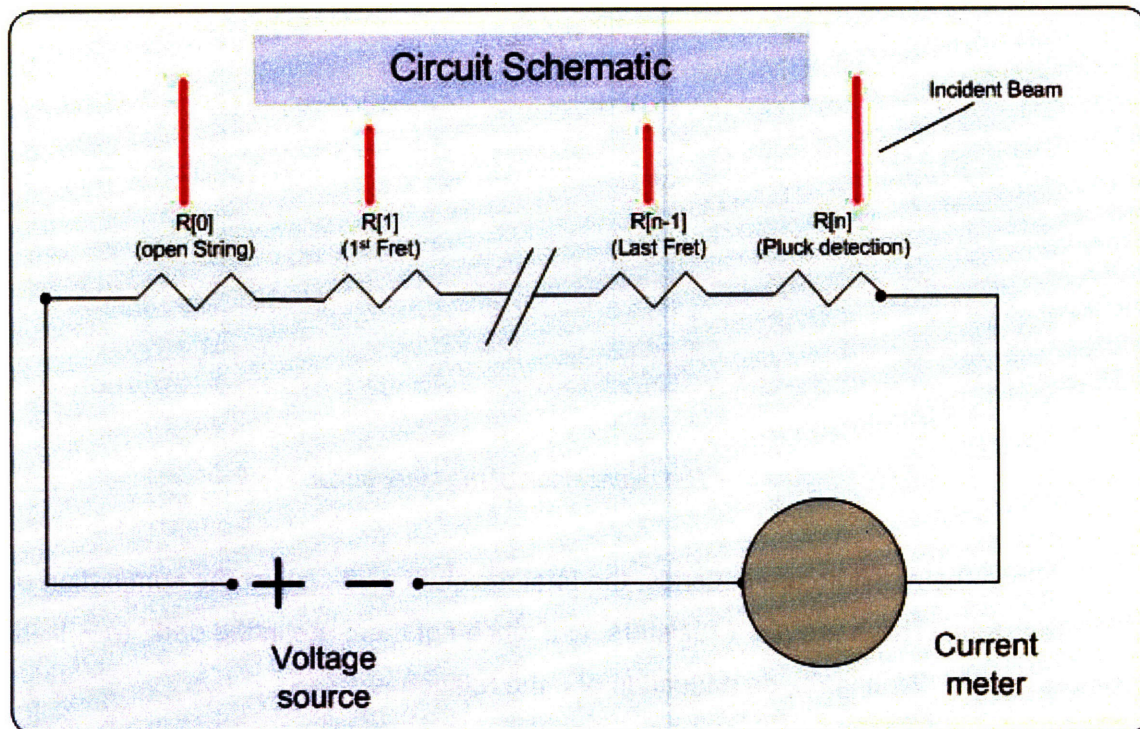


Figure 6 – Schematic of the photoresistors, battery and current reader.

The resistors are all in series. With n frets, there will be $n + 1$ resistors; one resistor for each fret and one at the end of the guitar to signify an open string. This gives us the $n + 2$ states needed to define the system, because of the case in which none of the resistors are in light.

Let f be the number of the fret that the blocking finger is behind (see fig 7). Therefore $f = 1$ means all the resistors are lit except the one at the end of the guitar, and $f = n+1$ blocks all the resistors (technically “in front of” the $n + 1$ fret, or more conceptually, beyond the last fret). In playing the guitar, f is the normal number assigned to a fret being played, but it is useful to view it as the number of resistors in the dark. (See appendix II for further explanation of the variable f .)

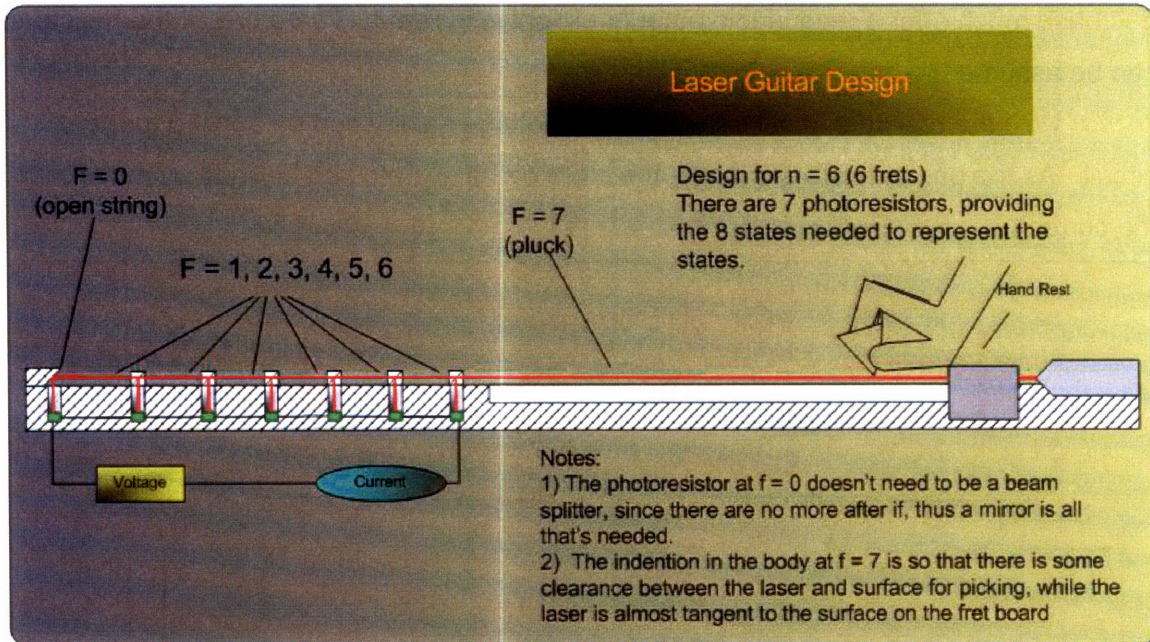


Figure 7 – The overall look of the laser guitar

Since the resistors are in series, the total resistance, R_T , is just the summation of all the resistors. There are $n + 1$ resistors, and since f of them are in the dark, $(n + 1 - f)$ resistors are lit. Writing R_T , as a function of f , the relation is

$$R_T = fR_D + (n + 1 - f)R_L - R_R \quad (\text{E1})$$

where R_R is the residual resistance from the wires and amp meter. This is simply adding all the resistances in the circuit taking into account the photoresistors up to f are in the dark. Since the measured parameter is the resistance, the inverse of (E1) is

$$f = \frac{R_T - (n + 1)R_L - R_R}{R_D - R_L} \quad (\text{E2})$$

Since the current through the system is measured, using Ohm's law $V_{\text{battery}} = IR_T$ the relationship can read

$$f = \frac{\frac{V_{\text{battery}}}{I} - (n + 1)R_L - R_R}{R_D - R_L} \quad (\text{E3})$$

This relationship provides the fret being played given the current (or resistance) through the circuit.

Equation 2 is a line giving a unique fret number for each reading of R . Since f is an integer this allows some room for error as it will be rounded. A characteristic graph of this is shown in figure 9.

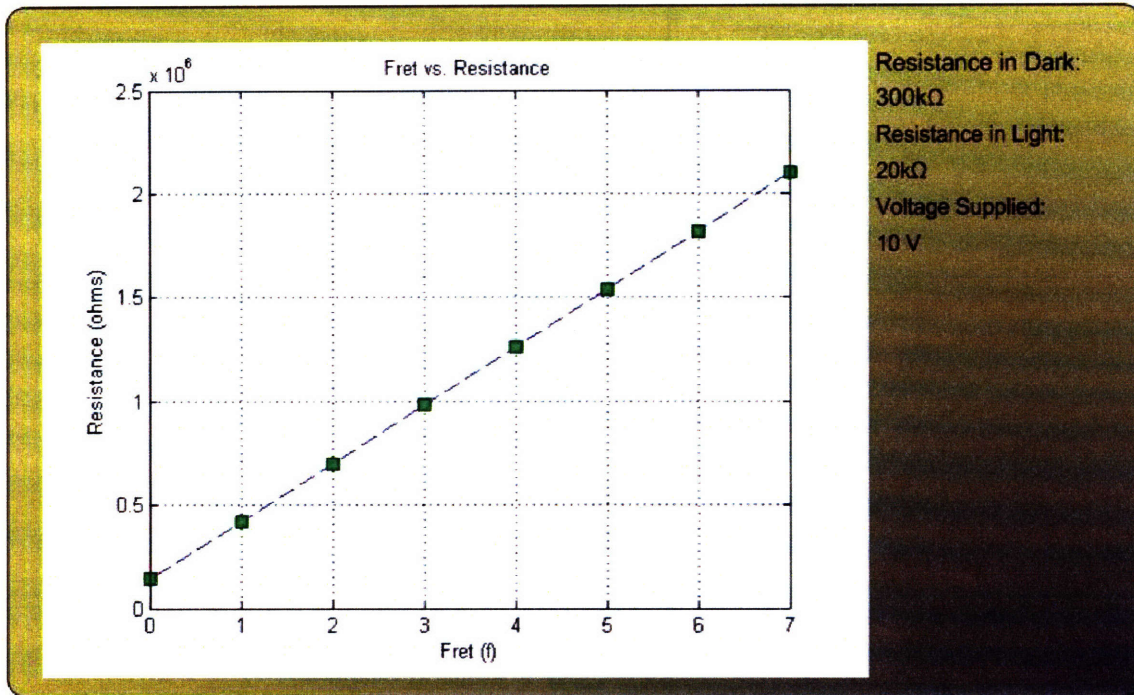


Figure 8 – Characteristic graph of the resistance resulting in different f positions.

Since f represents the number of lit resistors, the resistance is lower at low f values. The slope of the graph is $R_D - R_L$, so increasing the difference between these two parameters will better distinguish the different states. In order to steepen the slope to get clearer readings.

Laser Location

It is necessary for the lasers to approach the nut from the bridge. This allows the plucking priority. Except for when a pluck is blocking all the resistors, the guitar will be in a state representing one of the frets.

Also only the last fret (higher f value) being blocked should be taken into account. On a stringed guitar, the string is vibrated from the bridge to the first fret pressed down; frets behind this can be pressed in preparation for the next note without consequence on the current note. By having the laser approach from the bridge, the laser is blocked at the first finger hit, and it doesn't depend on what happens beyond that.

Playability

There are a few other improvements needed to make the guitar playable. In order to prevent the player's picking hand from inadvertently blocking the laser, a bridge should be made to rest the palm on (see fig 8). A U-shaped rigid sheet arching over the lasers should be attached near the laser emitter.

The body surface under the lasers should be cut down $\frac{1}{2}$ inches to provide clearance beneath the lasers. The fret board, though, needs the surface to be as close to the lasers as possible, to minimize the obstruction of the beam splitters.

The nut doesn't need a beam splitter. Since the beam shouldn't continue past the nut, a mirror should reflect the rest of the beam down onto the first resistor ($R[0]$).

Fret Spacing

Mimicking the structure of a real guitar is important, so that the only difference is the absence of strings. An important aspect of playing a guitar is that the frets are not evenly spaced out. Starting at the nut, spaces are wide, with each space narrowing towards the bridge. The reason for this is that the notes used in musical scales are spaced as a geometric progression.

The frequency of a vibrating string of length varies inversely as the length. By halving the length of the string the pitch is doubled. Converting from physics to music theory, doubling the pitch increases the note one octave. The Western chromatic scale is created by 12 notes. Assigning an arbitrary note the frequency of P , there are 12 notes in the geometric sequence reaching $2P$, the octave of P . Since this is 12 notes away:

$$Pr^{12} = 2P \rightarrow r = \sqrt[12]{2} \quad (\text{E4})$$

where r is the factor needed to multiply a pitch by to get the next note. Since the frequency varies inversely as the length, dividing the length of the string by r gives the length of the string required for the next note.

A stringed guitar has about 25 inch strings. In order to find the difference between frets, let the open string be L_0 in length, the string up to the first fret be L_1 , and so on. Let $\Delta L_{n,n+1}$ be the change in length from L_n to L_{n+1} . With r_{-1} representing the inverse of r , multiplying L_{n-1} gives the length of the next string ($r_{-1} = .9439$). Thus;

$$L_0 = 25in$$

$$L_1 = L_0 * r_{-1} \Rightarrow \Delta L_{0,1} = L_0 - L_1 = L_0(1 - r_{-1})$$

$$L_2 = L_1 * r_{-1} \Rightarrow \Delta L_{1,2} = L_1 - L_2 = L_0 r_{-1} (1 - r_{-1})$$

$$L_3 = L_2 * r_{-1} \Rightarrow \Delta L_{2,3} = L_2 - L_3 = L_0 r_{-1}^2 (1 - r_{-1})$$

$$\Delta L_{n-1,n} = L_0 r_{-1}^n (1 - r_{-1}) \quad \text{(E5)}$$

With this relation, the distance to the next fret can be found. (See the Appendix for a list of the lengths and spaces)

Challenges and Possible Solutions

There are some foreseeable difficulties in the further development of this project. Possible solutions are given below, but further research is required to fully test the them.

Response Time

The photoresisters take a few milliseconds to respond to the changes in light, defined as rise (from dark to light) and fall (from light to dark) times. The important dynamic element is the picking motion. During a pluck, all the photoresisters are in the dark, but only for the duration of the blocked beam. Unfortunately the fall time is the higher of the two, ranging from 40 to 100 milliseconds. This would only be a problem in the hands of the fastest guitarists, as the elite can pick at up to 20 times per second. This is just beyond the 50 millisecond threshold. This can be corrected for, though, by the software that interprets the current. When picked at any fret, the resistance will rise at a unique rate. By calibrating the guitar, the software could recognize when a pluck has occurred without depending on the resistors to fully respond.

Error in Beam Splitter Orientation

The laser must navigate through several beam splitters to reach the final photoresistors. Small angles of error at the beginning of the path could be magnified as the beam continues. This can be mediated by setting each beam splitter and making sure the beam hits the photoresistor beneath it. By doing this, the beam's slight crooks can be arranged to finally reach the last resistor.

Multiple Lasers

While this paper speaks generally of the case for one string, the guitar would need 6 laser beams; one for each string. The most straight forward way to accomplish this is to have the laser emitters side by side, pointed straight down the fret board (See Appendix IV for an alternative arrangement). This will require considerable effort in the construction, as each laser would need its own circuit of photoresistors, causing the need for 6 output currents and congesting the fret board with beam splitters and resistors.

Techniques not performable on Laser Guitar

The laser guitar, as this paper describes it, is incapable of many techniques common to the repertoire of guitarists. By simplifying the playing experience to the states of a pluck and holding each fret, much is ignored. Most, if not all, of these shortcomings could be augmented to the project with further development

The most important is the variation in volume, often called dynamics. The guitar just sends a signal of what fret is being played, and plays that note at the realization of a pluck, without knowing how loud to make it. This is a very important part of music, even warranting notation on musical scores to instruct how loud or soft to play a sequence of notes. This could be solved by measuring the time the plucking action occurred; if the time is small, then a very quick motion was used, implying a loud note, while long duration would imply soft notes. This though would require analysis of the dynamics of the resistors to know how fast the resistance changes when going from one state to another.

Although guitars have frets, allowing only incremental steps in pitches, rather than a spectrum of frequencies, by “bending” the string (pushing the string perpendicular to its direction) one can increase the tension in the string, allowing the pitch to increase in any increment. This is a very widely used technique, and would be a detriment to the laser guitar. An option to account for this would be to have a pedal that changes the pitch. This would make things a little more complicated as it would require another output to the computer.

Another technique that would be missed is palm muting. This is done by letting the picking hand rest on the bridge, slightly touching the strings, giving a less tonal and more percussive sound. This could be approximated by having the hand rest (described above) able to move up and down. By having a spring naturally push the piece away from the guitar body, the guitarist could exert pressure on it, implying a palm mute.

Other techniques that would take more development to implement are sliding, scratches, tapping, and harmonics.

Future Developments

This paper only conceives the physical aspects of the project. In order to function, software would be needed to interpret the current reading and produce sound. As it is currently designed, there is only one output from the guitar, the current in the photoresistor circuit, which defines all the states.

The actual current, though, will be more dynamic than the analysis in this paper assumes. The response time of the photoresistors will cause the current reading to lag slightly. By measuring the dynamic responses of switching from one state to another, one could empirically interpret the relationship between the current measured and the fret change being made.

There is also the issue of determining the power needed. Two sections of the design require power input; the lasers and the photoresistor circuit (figure 3). Since there are six lasers and six circuits, the power must be distributed among twelve systems.

Appendix

I. Graph of Illumination vs. Resistance.

This logarithmic graph shows how the luminous intensity (Lumens per square meter) relates to the resistance of the photoresistor. The linear appearance represents an exponential relation with resistance approaching a minimum value at high illuminance.

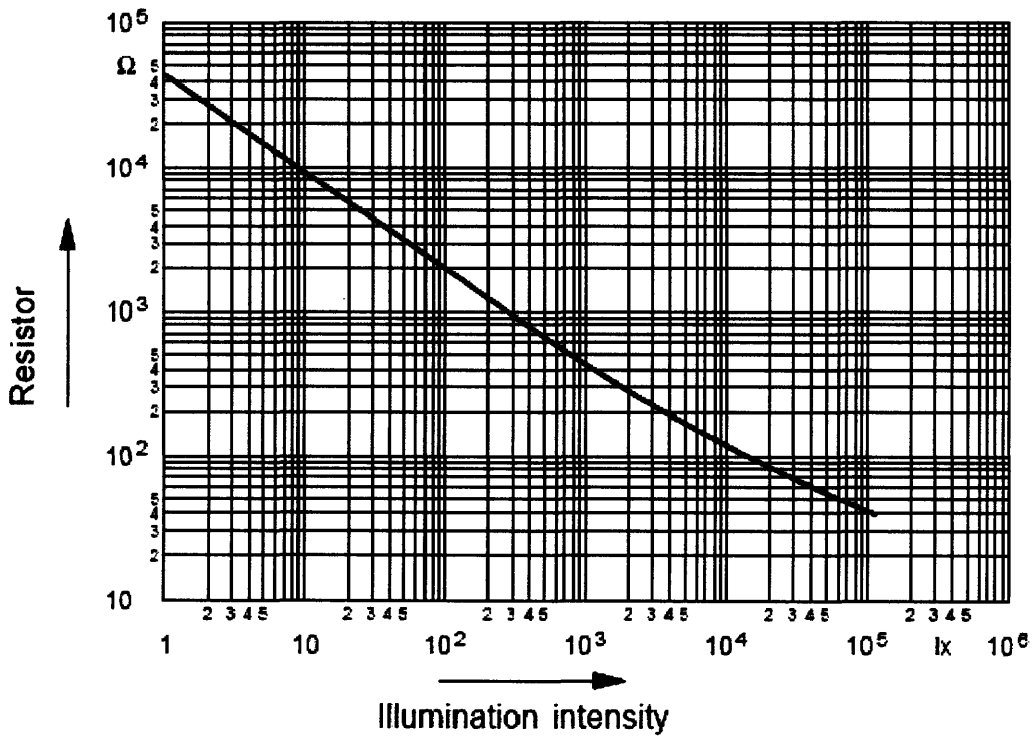


Figure 9 – Relation of Resistance to Illuminance.
(Graph courtesy of Festo Didactic [5])

II. The Variable f

The variable f used in this paper represents the location of the object blocking the beam, and consequently the state of the system. In figure 11, the state $f = 2$ is shown. In a guitar of n frets, there are $n + 2$ states needed to define; one state for each fret, the open string state, and the plucking state. Only $n + 1$ resistors are needed, since anywhere from 0 to all $n + 1$ of the resistors can be lit.

Since there are $n + 2$ states, f ranges $n + 2$ integers. Graph 2 shows the meaning of each f value.

Physical Meaning of all f Values (for a guitar with n frets)	
Value of f	Physical Meaning
0	Open string (all resistors lit)
1	First fret being played
2	Second fret
...	...
$n - 1$	Second to last fret
n	Last fret played
$n + 1$	Pluck (occurs beyond last fret)

Table 2 – List of all f values with their physical representation. Note this is very similar to table 1, since f represents the states.

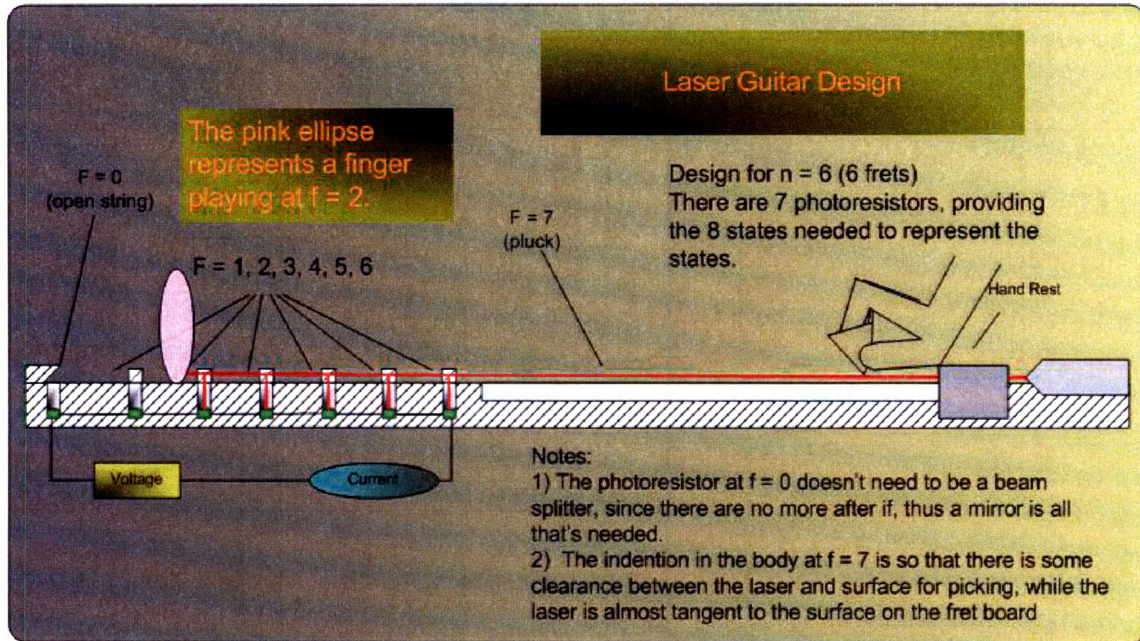


Figure 10 – Reprint of figure 7 showing the location of f =2

III. Length between Frets

Using equation 5 allows calculation of the natural distance from a fret to the next. Mimicking the fret spacing of a stringed guitar isn't required for the functionality of the laser guitar, but its important for the playability to remain similar.

Table 3 lists out the length of the string to each fret and the distance from each fret to the next.

The notation used:

- 1) L_n represents the length from the bridge to the n^{th} fret. 0 represents the nut, so L_0 is the length from the bridge to the nut, or the open string.
- 2) $\Delta L_{n-1,n}$ represents the space between the frets n and $n - 1$. Therefore $\Delta L_{0,1}$ is the space between the nut and the first fret.

The values in Table 3 were found by using equation 4 recursively using equation 4.

Lengths between frets			
(Based on full string length of 25 in.)			
$L_0 = 25$ in.	-	$L_7 = 16.68$ in.	$\Delta L_{6,7} = .99$ in.
$L_1 = 23.60$ in.	$\Delta L_{0,1} = 1.40$ in.	$L_8 = 15.75$ in.	$\Delta L_{7,8} = .94$ in.
$L_2 = 22.27$ in.	$\Delta L_{1,2} = 1.32$ in.	$L_9 = 14.86$ in.	$\Delta L_{8,9} = .88$ in.
$L_3 = 21.02$ in.	$\Delta L_{2,3} = 1.25$ in.	$L_{10} = 14.03$ in.	$\Delta L_{9,10} = .84$ in.
$L_4 = 19.84$ in.	$\Delta L_{3,4} = 1.18$ in.	$L_{11} = 13.24$ in.	$\Delta L_{10,11} = .79$ in.
$L_5 = 18.72$ in.	$\Delta L_{4,5} = 1.11$ in.	$L_{12} = 12.50$ in.	$\Delta L_{11,12} = .74$ in.
$L_6 = 17.68$ in.	$\Delta L_{5,6} = 1.05$ in.	-	-

Table 3 – Length between frets. Lists all lengths from the nut to its octave. Note L_{12} is half of L_0 since this represents an octave; the string is halved to double the pitch.

IV. Alternative Laser Arrangement

By splitting the beam, its possible to only use one laser. The easiest way accomplish this would be to use an array of beam splitters similar to the system on the fret board.

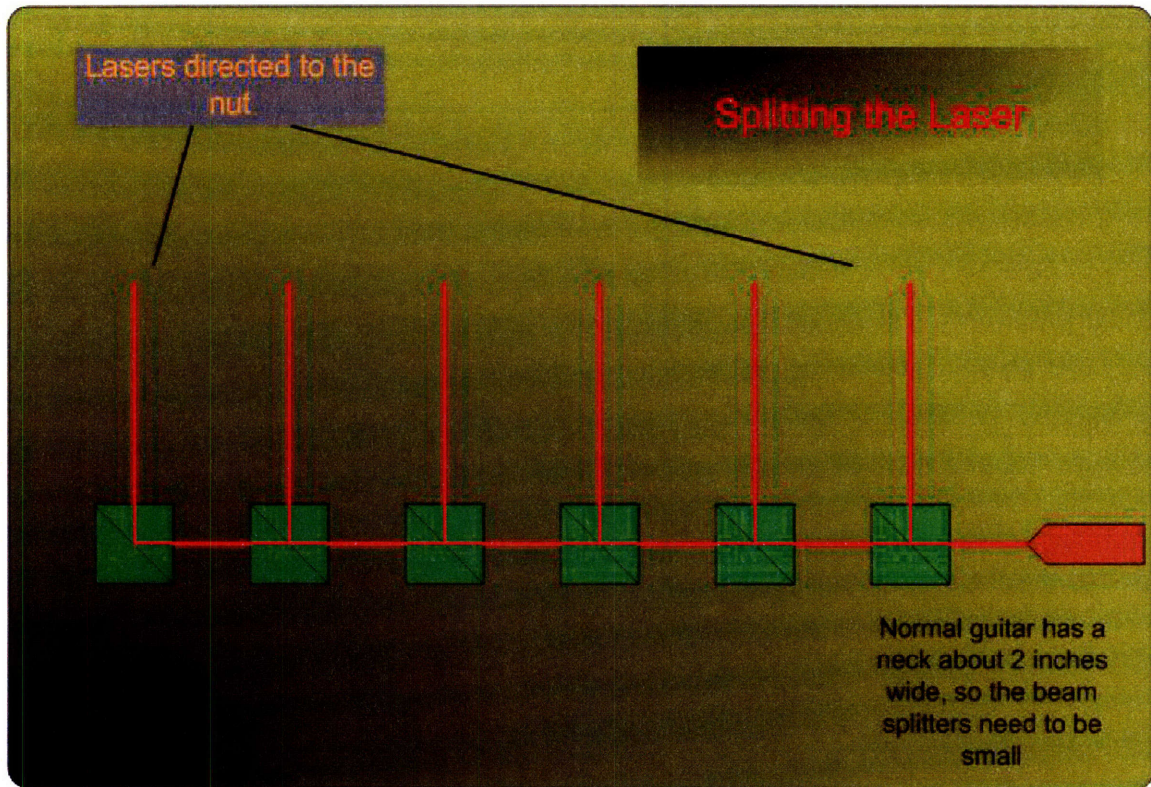


Figure 11 – Example of splitting one beam into the six strings needed.

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Course: 2.71 Optics

2. <http://www.musiciansfriend.com/>

Provided information on dimensions and materials of guitars and strings

3. <http://www.elixirstrings.com/>

4. <http://www.digikey.com/>

Provided information on typical photoresistors

5. <http://www.festo-didactic.com/int-en/>

Graph of Resistance vs. Illuminance:

<http://www.festo-didactic.com/ov3/media/customers/>

1100/00296860001075223684.pdf