

# Diodes

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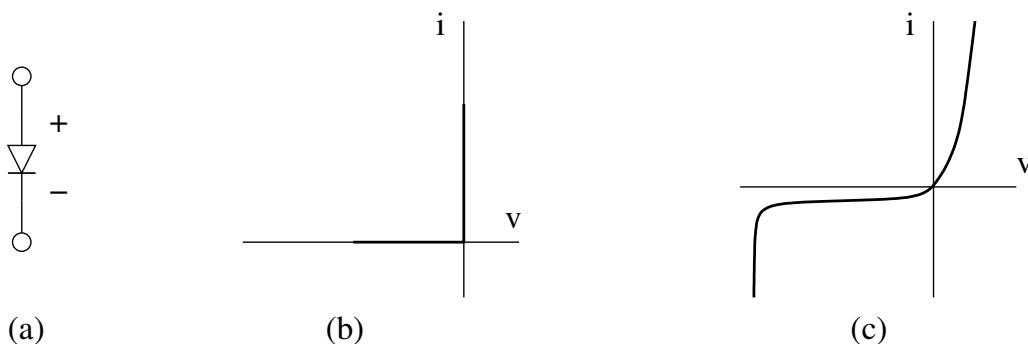
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## 1 Introduction

A diode is a dispositive made of a semiconductor material, which has two terminals or electrodes (di-ode), that act like an on-off switch. When the diode is “on”, it acts as a short circuit and passes all current. When it is “off”, it behaves like an open circuit and passes no current. The two terminals are different and are marked as plus and minus in figure 1. If the polarity of the applied voltage matches that of the diode (forward bias), then the diode turns “on”. When the applied voltage polarity is opposite (reverse bias), it turns “off”. Of course this is the theoretical behaviour of an ideal diode, but it can be seen as a good approximation for a real diode.

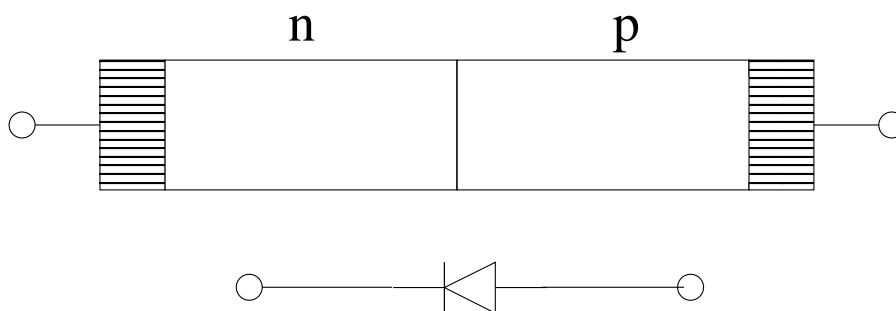
A diode is simply a *pn* junction (see 'Introduction into Semiconductor Physics') with the following characteristics:

- Under forward bias, it needs a small voltage to conduct. This voltage drop is maintained during conduction.
- The maximum forward current is limited by heat-dissipation ability of the diode. Usually it is around 1000 *mA*.
- There is a small reverse current.



**Figure 1:** (a) Diode symbol. (b) Current-voltage characteristics of an ideal diode. (c) IV curve for a real diode.

- Every diode has a maximum reverse voltage (breakdown voltage) that cannot be exceeded without diode damage.



**Figure 2:** A  $p - n$  diode junction structure and the equivalent device schematics.

## 1.1 Diode equation

### 1.1.1 Reverse Bias

When the diode is reverse-biased, a very small drift current due to thermal excitation flows across the junction. This current (reverse saturation current,  $I_0$ ) is given, according to the Boltzmann equation, by the formula:

$$I_0 = K_0 e^{-\frac{eV_0}{kT}}$$

where  $K_0$  is a constant depending on the  $pn$  junction geometry and  $V_0$  is the built-in voltage of the diode (see chapter “Semiconductor Materials: pn junction”).

### 1.1.2 Forward Bias

When the diode is forward-biased through a voltage  $V$ , a small drift current flows again across the junction. In that case, however, there is an additional component, the diffusion current  $V_d$ , given by the formula:

$$I_d = K_0 e^{\frac{e(V-V_0)}{kT}}$$

These two currents have opposite directions, the total current is therefore given by:

$$I = I_d - I_0 = K_0 e^{-\frac{eV_0}{kT}} (e^{\frac{eV}{kT}} - 1) = I_0 (e^{\frac{eV}{kT}} - 1)$$

## 1.2 General Diode Specifications

There are four diode ratings that apply in one way or another to all types of diodes and applications:

1. *Forward voltage drop*  $V_F$ : is the forward-conducting junction level ( $\sim 0.7$  V for Si diodes and 0.3 V for Ge diodes)<sup>1</sup>.
2. *Average forward current*  $I_F$ : is the maximum amount of forward current that the diode can carry for an indefinite period. If the average current exceeds this value, the diode will overheat and, eventually, will be destroyed.
3. *Peak reverse voltage*  $V_R$ , or reverse breakdown voltage. This is the largest amount of reverse-bias voltage the diodes's junction can withstand for an indefinite period of time. If a reverse voltage exceeds this level, the voltage will punch through the depletion layer and allow current to flow backwards through the diode, which is a destructive operation (except for the case of a Zener diode).
4. *Maximum power dissipation*  $P$ . The actual diode power dissipation is calculated multiplying the forward voltage drop and the forward current. Exceeding the maximum power dissipation will result in thermal breakdown of the diode.

Excessive forward current and reverse breakdown voltage are the most common causes of diode failure. In both cases the diode gets very hot, what destroys the *pn* junction. Occasional peaks of voltage or current exceeding these rates for very short times (few milliseconds) may not overheat the junction, but repeated peaks may fatigue the junction. By design, diodes are selected with ratings that exceed two or three times the expected peaks in the circuit.

## 2 Types of diodes

We can distinguish the following types of diodes:

- Rectifier diodes are typically used for power supply applications. Within the power supply, you will see diodes as elements that convert AC power to DC power;
- Switching diodes have lower power ratings than rectifier diodes, but can function better in high frequency application and in clipping and clamping operations that deal with short-duration pulse waveforms;

<sup>1</sup>This is the case in the so-called "constant-voltage-drop" or "0.7-V" model. In that model, the current is a step function of the voltage: if the forward voltage is less than 0.7 V, the current which flows through the junction is zero, if the forward voltage is greater than 0.7, then the voltage drop in the diode is always 0.7 V (in the case of silicon)

- Zener diodes, a special kind of diode that can recover from breakdown caused when the reverse-bias voltage exceeds the diode breakdown voltage. These diodes are commonly used as voltage-level regulators and protectors against high voltage surges;
- Optical diodes;
- Special diodes, such as varactors (diodes with variable capacity), tunnel diodes or Schottky diodes.

## 2.1 Rectifier diodes

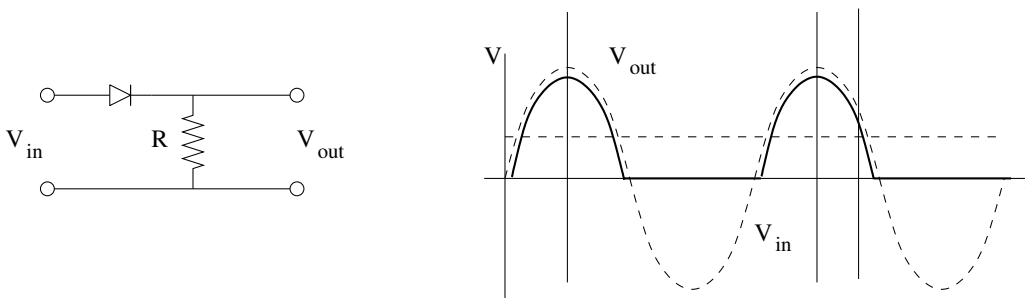
A rectifier is a dispositive that ideally transforms the AC input voltage into a DC voltage (voltage is always positive or zero). These diodes have the largest ratings and sometime can be quite big in volume. As a rule of thumb, the bigger the diode (more *pn* surface junction available for heat dissipation), the higher the ratings.

### 2.1.1 Half-wave rectifier

A half-wave rectifier is composed of a single diode that connects an AC source to a load. In figure 3 the load is represented by a resistor. The diode conducts on AC voltage only when its anode is positive with respect to the cathode (i.e. greater than 0.7 V for a silicon diode). The output has therefore only a positive component with an average value:

$$V_{ave} = \frac{1}{T} \int_0^{T/2} V_p \sin wt \, dt = \frac{V_p}{\pi}$$

The output peak voltage is the AC source minus the voltage drop of the diode, that in most cases can be neglected.



**Figure 3:** Half wave rectifier. Note the effect of the 0.7 V diode voltage drop. If  $V_p \gg 0.7V$ , it can be neglected.

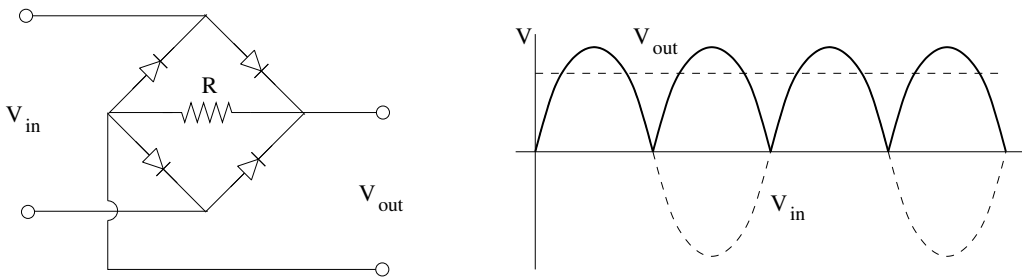
### 2.1.2 Full-wave rectifier

In half-wave rectifiers, half of the power provided by the source is not used. To solve this problem, we have to use full-wave rectifiers. The minimum full-wave rectifier is composed of two diodes, but it requires a center tapped transformer. Figure 4 shows a bridge rectifier, composed of four diodes, that can use a “normal” transformer.

The AC current, according to its direction, flows either in the top or in the bottom part of the bridge in each half-cycle. In the output voltage we will have a component for both negative and positive parts of the input voltage. In both cases the current passes through two forward-biased diodes in series, what produces a voltage drop of 1.4 V.

The average voltage of a full-wave rectifier is:

$$V_{ave} = \frac{1}{T/2} \int_0^{T/2} V_p \sin wt \, dt = \frac{2V_p}{\pi}$$



**Figure 4:** Full wave rectifier. In this case the voltage drop, not shown in the graphic, will be 1.4 V because two diodes are crossed.

### 2.1.3 Rectifier filters

The waveforms generated directly by the rectifiers described above, are not very useful, but can be smoothed to produce almost perfect DC. For that purpose we can use the inertia properties of capacitors and inductors.

Although the capacitor does a good job producing DC, a significant ripple voltage remains. During the discharging period, the capacitor voltage reduces exponentially. At the end of the discharge, the output voltage is:

$$V_{out} = V_p e^{-(t_2-t_1)/R_L C}$$

The discharging time is  $t_2 - t_1 \sim T$ , so the ripple voltage is:

$$v_r = \Delta V = V_p - V_p e^{-T/R_L C} \simeq V_p \frac{T}{R_L C} = \frac{V_p}{\nu R_L C}$$

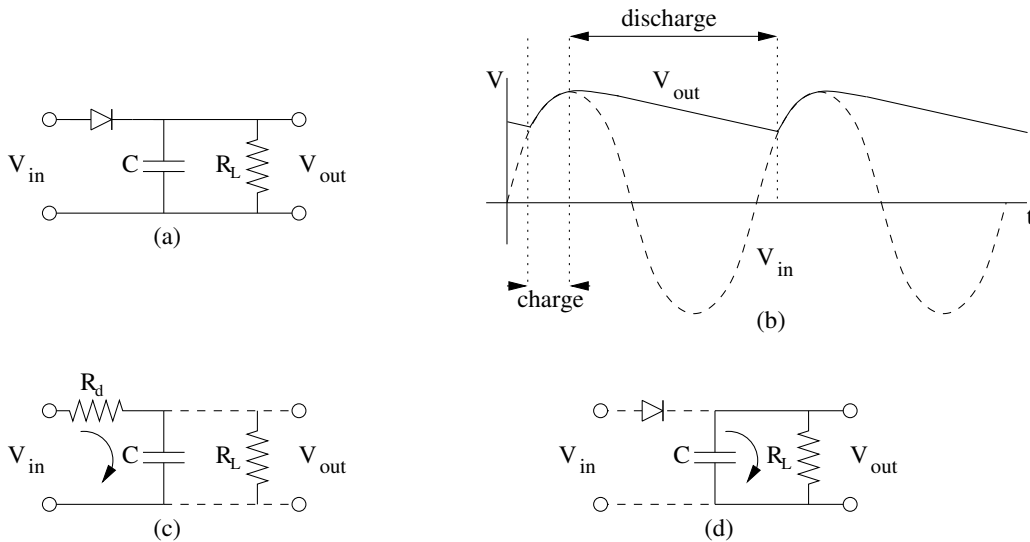
In case of a full-wave rectifier the ripple voltage is:

$$v_r = V_p \frac{T}{2R_L C} = \frac{V_p}{2\nu R_L C}$$

### 2.1.4 An application of rectifiers

A significant problem for electrostatic accelerators is the production of sufficiently high accelerating voltages. At the beginning of the 1930s, Cockroft and Walton<sup>2</sup> developed a high

<sup>2</sup>J.D. Cockroft, E.T.S. Walton, *Proc. Roy. Soc.*, **A136**, 619 (1932), **A137**, 229 (1932), **A144**, 704 (1934)



**Figure 5:** Filters: (a) A capacitor in parallel with the load resistance will smoothen the DC output. (b) The smoothed voltage. The circuit during (c) charging and (d) discharging of the capacitor.

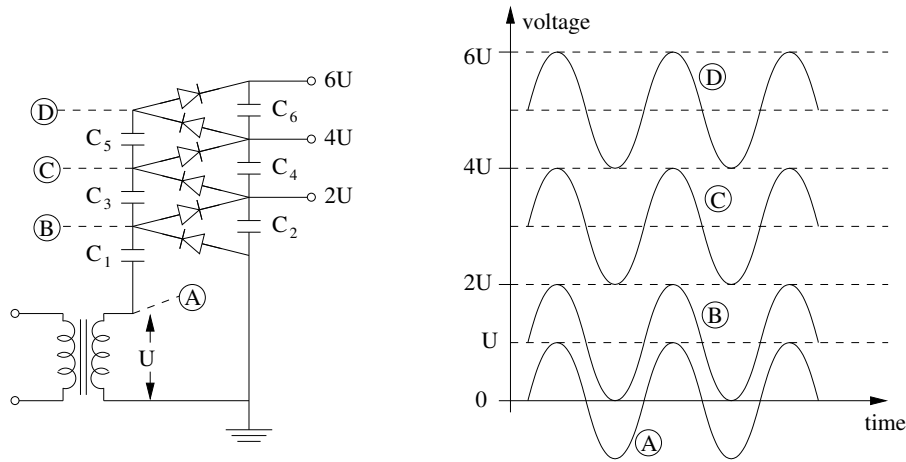
voltage generator based on a system of multiple rectifiers. At their first attempt they achieved a voltage around 400000 V. The operation of this generator<sup>3</sup>, also known as Greinacher circuit, is explained in figure 6. At point A a transformer produces a sinusoidally varying voltage  $U(t) = U \sin \omega t$  of frequency  $\omega$ . The first rectifying diode ensures that at point B the voltage never goes negative. Thus the capacitor  $C_1$  charges up to a potential  $U$ . At point B the voltage now oscillates between the values 0 and  $2U$ . The capacitor  $C_2$  is then charged up via the second rectifier to a potential of  $2U$ . In the same way as before, the third diode ensures that the potential at point C does not fall below  $2U$ . Here it varies between  $2U$  and  $4U$ , and so with the help of the fourth rectifier a voltage of  $4U$  is generated. The pattern is repeated, with many such rectifier stages arranged one after another. Without loading, the maximum achievable voltage is then  $2nU$ , where  $n$  is the number of rectifier stages.

During operation, a current  $I$  is always drawn from the generator. This discharges the capacitors slightly when the diodes are in reverse bias, leading to a somewhat lower generated voltage than the one simply expected from the number of rectifier stages. The current-dependent voltage generated by the cascade circuit is given more exactly by the relation

$$U_{tot} = 2Un - \frac{2\pi I}{\omega C} \left( \frac{2}{3}n^3 + \frac{1}{4}n^2 + \frac{1}{12}n \right)$$

It is immediately apparent that a high capacitance  $C$  and a high operating frequency  $\omega$  strongly reduce the dependence on the current.

<sup>3</sup>Schenkel, *Elektrotechn. Z.*, **40**, 333 (1919), H. Greinacher, *Z. Physik*, **4**, 195 (1921)

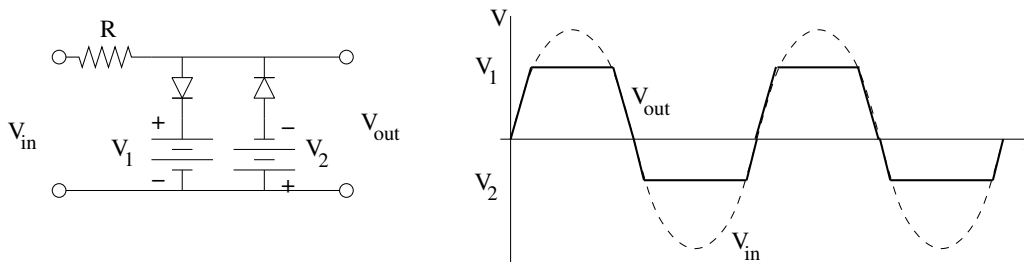


**Figure 6:** Schematic drawing explaining the operation of the Cockcroft-Walton cascade generator.

## 2.2 Switching diodes

### 2.2.1 Clipping

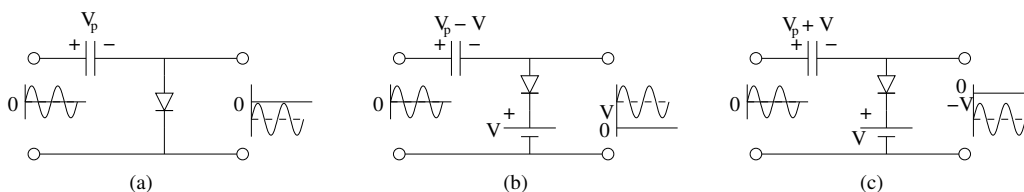
The function of a clipping circuit is to cut off part of an input waveform.



**Figure 7:** Clipping principle.

### 2.2.2 Clamping

If the DC value of a signal needs to be changed, a capacitor can be charged with the appropriate value. When connected in series with the signal source, it will then provide the desired DC level.



**Figure 8:** Clamping principle.

For positive values of the input signal, the diode immediately conducts, allowing the capacitor to be charged. The  $RC$  time constant is small because the only resistor present is the small internal resistor of the diode (less than  $1\ \Omega$ ). For negative values of the input signal, the diode is reverse-biased, so the capacitor cannot be discharged, maintaining the potential. In general, if we use a battery of voltage  $V$ , the output signal will be:

$$V_{out} = -V_p + V + V_p \sin \omega t = V_p(\sin \omega t - 1) + V$$

## 2.3 Zener diodes

A conventional solid-state diode will not let current flow up to its breakdown voltage if reverse-biased. By exceeding the breakdown voltage, a conventional diode is destroyed during breakdown due to excess current and overheating. In case of forward-bias (in the direction of the arrow), the diode exhibits a voltage drop of roughly  $0.7\ \text{V}$ . The voltage drop depends on the type of the diode.

A Zener diode exhibits almost the same properties, except the device is especially designed so as to have a greatly reduced breakdown voltage, the so-called Zener voltage. A Zener diode contains a heavily doped  $pn$  junction allowing electrons to tunnel from the valence band of the  $p$ -type material to the conduction band of the  $n$ -type material. A reverse-biased Zener diode will exhibit a controlled breakdown and let the current flow to keep the voltage across the Zener diode at the Zener voltage. For example, a  $3.2\ \text{V}$  Zener diode will exhibit a voltage drop of  $3.2\ \text{V}$  if reverse biased. However, the current is not unlimited, so the Zener diode is typically used to generate a reference voltage for an amplifier stage. The breakdown voltage can be controlled quite accurately in the doping process. Tolerances up to  $0.05\%$  are achievable, though the most widely used tolerances are  $5\%$  and  $10\%$ . The effect was discovered by the American physicist Clarence Melvin Zener. In figure 9, the Zener behaviour is illustrated:

## 2.4 Optical diodes

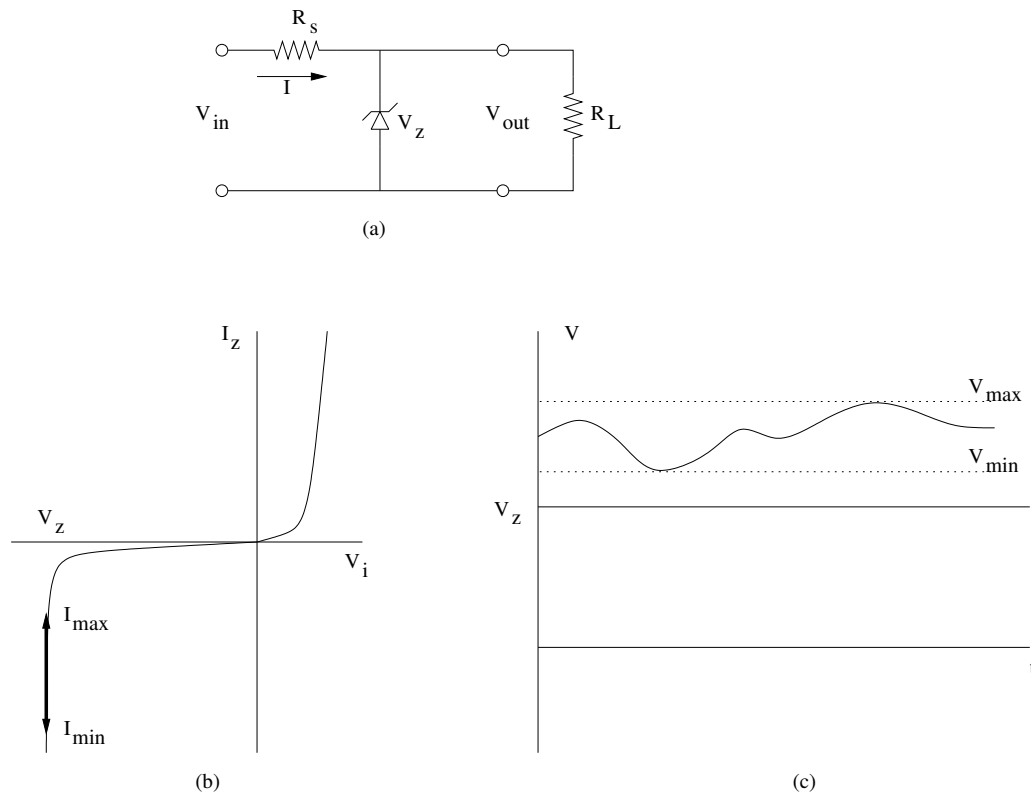
### 2.4.1 LED (Light Emitting Diode)

A light-emitting diode (LED) is a semiconductor device that emits incoherent monochromatic light when electrically biased in the forward direction. The colour depends on the semiconducting material used, and can be near-ultraviolet, visible or infrared. The wavelength of the light emitted, and therefore its colour, depends on the bandgap energy of the materials forming the  $pn$  junction. A normal diode, typically made of silicon or germanium, emits invisible far-infrared light. Currently used materials for LEDs are gallium arsenide (GaAs) for the infrared, gallium arsenide phosphide (GaAsP) for yellow and red light, and gallium phosphide (GaP) for red and green light. The intensity of the light depends on the current that passes through the LED.

### 2.4.2 Photodiode

A photodiode is a diode working in reverse polarization and having a window where the light can enter and hit directly the  $pn$  junction. As in the case of the LED, the energy level of the impurities has been chosen in order to allow electrons to jump from valence to conduction





**Figure 9:** (a) A voltage regulator is inserted between the input voltage and the load. (b) The Zener current  $I_z$  varies between  $I_{max}$  and  $I_{min}$  in response to the varying input voltage so as to keep the load current and the load voltage constant (c).

band. In the absence of light the leakage current is negligible, but when light is present, the leakage current increases to measurable values.

### 2.4.3 Optocoupler

An optocoupler is a device that combines a LED and a photodiode in such a way that the light emitted by the LED hits the photodiode. LED and photodiode can be connected to different circuits, so this device allows to send a signal between two isolated networks coupled just through light emission and reception.

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