Photorelays ~Points for photorelays in high frequency circuit applications ~

Overview

Photorelays (MOSFET output photocouplers) have a variety of advantages, and replacement from mechanical relays is progressing. However, there are some points that must be taken into consideration in comparison with mechanical relays when they are used in high-frequency circuits such as semiconductor testers and measuring instrument applications.

This document mainly describes precautions when controlling high-frequency signals with photorelays.

Here, signals with a frequency ranging from several hundred MHz to several hundred GHz are positioned as high-frequency signals. In addition, assume that a 1-Form-A photorelay (a photorelay in which the output-side MOSFET is turned on when the input-side LED signal is on) is used as a precondition.

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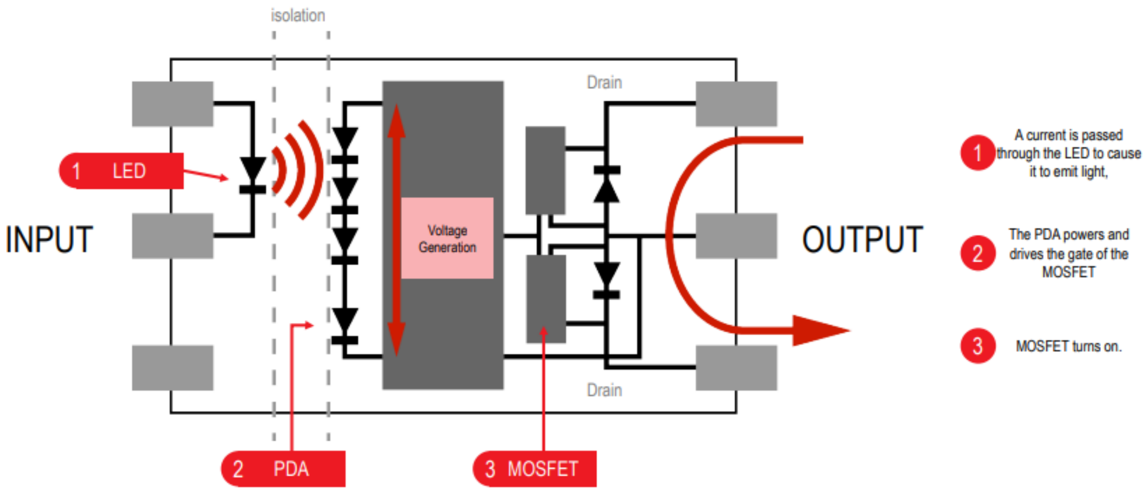
1. Introduction

A photorelay is a semiconductor relay with MOSFETs at the output stage (Fig. 1). Table 1 shows feature comparison between photorelays and mechanical relays.

Recently, reliability has become important and packages of photorelays have become smaller, the replacement from mechanical relays is progressing in terms of space saving. However, there is a resistance component (on-resistance R_{ON}) when a photorelay is on compared with a mechanical relay, and a capacitance component (output capacitance C_{OFF}) mainly from the PN junction capacitance of the parasitic diode on the output side MOSFETs when the a photorelay is off (Fig. 2). As the frequency increases, the inductance (L) component can also be seen (Fig. 3). Consideration should be given to replacing mechanical relays with photorelays in circuits that transmit high-frequency signals. This application note mainly describes precautions when controlling high-frequency signals with photorelays.



(1) When current is applied to the LED on the input side, the LED emits light and an optical signal is generated.

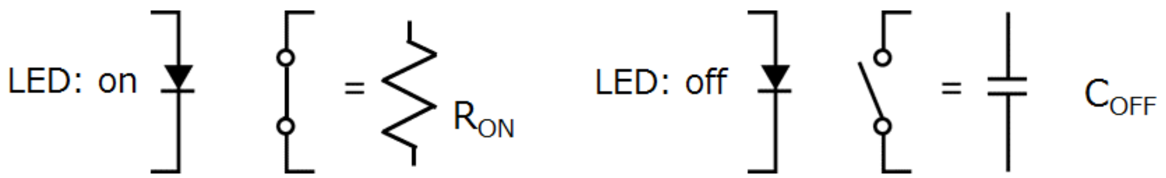
(2) The optical signal is converted into an electrical signal by the contact-side PDA and the MOSFETs. Input the electrical signal to the control terminal (gate).

(3) When the electric signal is input to the gate, MOSFETs are turned on, and the contact is connected.

Fig. 1 Principles of operation of photorelay (1-Form-A contact)

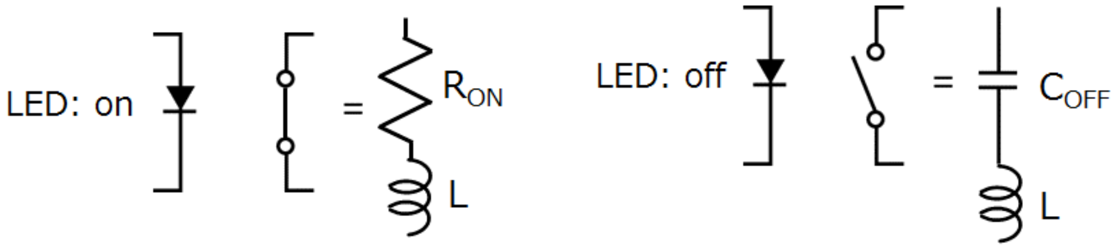
Table 1 Comparison between photorelays and mechanical relays

	Mechanical relay (Signal relay)	Photorelay	Remarks (Feature of Photorelay)
Lifetime	△ (With contact limit)	◎ (No contact limit)	Long life
Contact Capacity	◎(2A) ※Ta 85℃/AC･DC applicable	〇 (~5A) ※Ta 25℃/VOFF=60V basis	
Contact Resistance (ON Resistance)	About 0.1Ω (Degraded by On/Off)	About 0.02~25Ω (Stable)	High reliability
Contact Voltage (OFF Voltage)	◎ (ex : AC 250V, DC 30V)	〇 (ex : line up with 20V~600V)	
Isolation Voltage	〇 (ex : 1KVrms)	◎ (max:5KVrms)	
Operation / Release Time	△ About 5ms	〇 About 0.1ms	High speed
Operation Sound	△(exist)	◎(No sound)	No noise
Miniaturization	〇 (ex : $60mm^2$)	◎ (S-VSON: $2.9mm^2$ - 1.45 × 2.0 mm)	Smaller size
Input Power Consumption	× (coil) 100mW~	◎ (LED) (ex: 0.5mW~)	Less power consumption
Contact Form	1c、2c	1a、1b、2a、1a1b	
Leakage Current	◎(not exist)	〇(20pA~)	



(a) LED: on (Contact: on) (b) LED: off (Contact: off)

Fig. 2 R_{ON} and C_{OFF} of the photorelay output part



(a) LED: on (Contact: on) (b) LED: off (Contact: off)

Fig. 3 Inductance (L) components also appear in a high frequency

2. Photorelay behavior for high frequency signals

As described above, the photorelay has an on-resistor (R_{ON}) and a pin-to-pin capacitance (C_{OFF}). This is a major difference from mechanical relays.

When the specified current and voltage are applied to the photorelay input, the photorelay turns on. At this time, MOSFETs of the output stage behaves as a resistance component when the applied current frequency ranges from DC to low frequency. However, as the frequency increases, an inductance component appears in addition to the resistance component. On the other hand, if no biasing is applied to the photorelay input, the output MOSFETs are turned off. At this time, MOSFETs are equivalent to the capacitance component when the applied signal frequency ranges from DC to low frequency, but an LC resonance occurs because the inductance component appears in addition to the capacitance component as the frequency increases. Note this when controlling high frequency signals with a photorelay. In other words, the signal after passing the photorelay is distorted with respect to the expected output signal. A common parameter for expressing this distortion is the S-parameter, which is described later.

3. Points when using photorelays in high-frequency circuits

A problem when operating photorelay is the transmission characteristics when the output is turned on.

When the frequency increases, the output waveform rise time (t_{rout}) after passing through the photorelay changes from the input waveform rise time (t_{rin}) due to effects of inductance components of the photorelay. This change is expressed as the equivalent rise time (ERT: Equivalent Rise Time). The ERT is defined by the equation shown in Fig. 4. The smaller the value, the less the change in the signal is, which can be said to be a good characteristic. The transmission characteristics can also be expressed using the S-parameter described later.

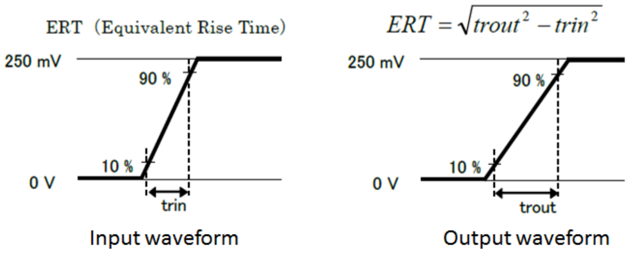


Fig. 4 Transmission characteristics

A leakage current is also a problem when the output (contact) of the photorelay is turned off. When a steep rising voltage is applied to the contact when the photorelay is turned off, a leakage current is generated (Fig. 5). Approximately, $I_L = C_{OFF} \times dV/dt_r$ flows. An impedance, the total opposition to alternating current by an electrical circuit, which corresponds to the resistance in a DC circuit. This impedance at C_{OFF} decreases as the frequency increases, then the leakage current increases. In such cases, it is recommended to use a product with smaller C_{OFF}.

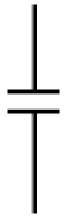
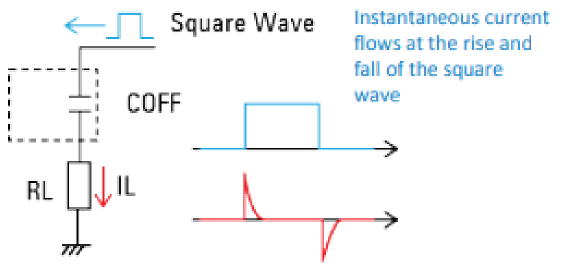
Mode	Equivalent Circuit	Operation Example
LED : OFF	Capacitor 	

Fig. 5 Leakage current when the contact is turned off

4. S-parameters (Scattering Parameters)

S-parameters are one of circuit parameters used to represent the characteristics of high frequency electronic circuits and components. The S-parameters are expressed in a matrix (S-matrix), which represents the electrical power characteristics of the network's transmission (signal is transmitted through the network) and reflection (signal is returned from the network).

<Definition of two-port network>

S-parameters are often used in a network with two pairs of terminals (two-port circuit, or four-terminal network), and is defined as follows when the input terminal pair is a terminal pair and the output terminal pair is a terminal pair 2 (Fig. 6). The definitions of the symbols are as follows.

a_1: Square root of the incoming power wave from the port 1 (Note)
b_1: Square root of the outgoing power wave to the port 1
a_2: Square root of the incoming power wave from the port 2 (Note)
b_2: Square root of the outgoing power wave to the port 2

(Note) 0 dBm = 1 mW is used for our measurement

S_{11}: Signal reflection ratio at the port 1. This ratio can be measured in decibels and it means the return loss at the port 1.
S_{21}: Signal transmission ratio from the port 1 to the port 2. This ratio can be measured in decibels and it means the intertion loss (isolation).
S_{12}: Signal transmission ratio from the port 2 to the port 1. This ratio can be measured in decibels and it means the intertion loss (isolation).
S_{22}: Signal reflection ratio at the port 2. This ratio can be measured in decibels and it means the return loss at the port 2.

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} S_{11}a_1 + S_{12}a_2 \\ S_{21}a_2 + S_{22}a_2 \end{bmatrix}$$

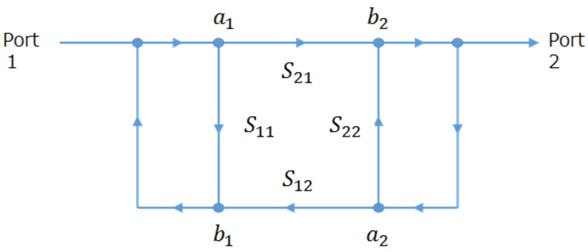


Fig. 6 S-parameters and signal flow graph

4.1 S-parameters for photorelays

When the signal frequency increases, signal loss at the photorelay contact become large, which may cause of inaccurate signal transmission or heat generation.

Therefore, controlling a high frequency, it is necessary to select a photorelay having low signal loss (low insertion loss) when the contact is closed (photorelay; on) and low signal leakage (high isolation) when the contact is open (photorelay; off). When selecting photorelays, the insertion loss and the isolation are typically required from S-parameters measuerment results.

1. Signal loss when the photorelay is on (insertion loss)
2. Signal loss when the photorelay is off (isolation)

From the above, a photorelay with low R_{ON} or low C_{OFF} is required to control high frequency.

Product examples) Low R_{ON} type: TLP3475 / TLP3475S Low C_{OFF} type: TLP3440 / TLP3440S

4.2 Insertion loss (LED: on)

The insertion loss corresponds to the resistance between the photorelay output terminals when it is on. Signal loss occurs between the terminals at high frequencies when the photorelay is on. The magnitude of the loss is called insertion loss, which is expressed in dB (decibels) as the ratio of the input power P_{in} and the output power P_{out}.

The insertion loss is calculated by the formula below. Large negative value means high magnitude loss. As the frequency increases, the negative value of the insertion loss increases due to the influence of the inductance components (Fig. 7). This means that the transmission efficiency is poor.

$$\text{Insertion loss (dB)} = 10log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

Examples) -0.1 dB: Approx. 2 % signal loss　-1.0 dB: Approx. 20 % signal loss
-3.0 dB: Approx. 50 % signal loss　-6.0 dB: Approx. 75 % signal loss

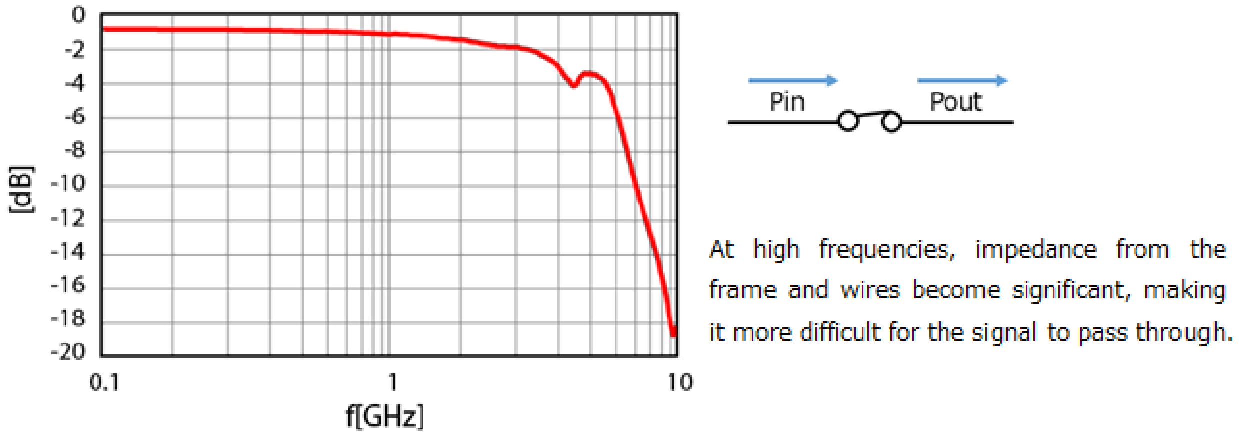


Fig. 7　Insertion characteristics

4.3　Isolation (LED: off)

The insertion corresponds to the resistance between the photorelay output terminals when it is off. At high frequencies, signal passes (leakage) the C_{OFF} even in the off-state. The magnitude of the leakage is called isolation, which is expressed in dB (decibels) as the ratio of the input power P_{in} and the output power P_{out}.

The isolation is calculated by the formula below. The large negative value means less leakage. As the frequency increases, the leakage increases, so the isolation value increases (Fig. 8).

$$\text{Isolation (dB)} = 10log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

Examples) -10 dB: 1/10 (10 %) signal leakage　-20 dB: $1/10^2$ (1 %) signal leakage
-30 dB: $1/10^3$ (0.1 %) signal leakage　-60 dB: $1/10^6$ (0.0001 %) signal leakage

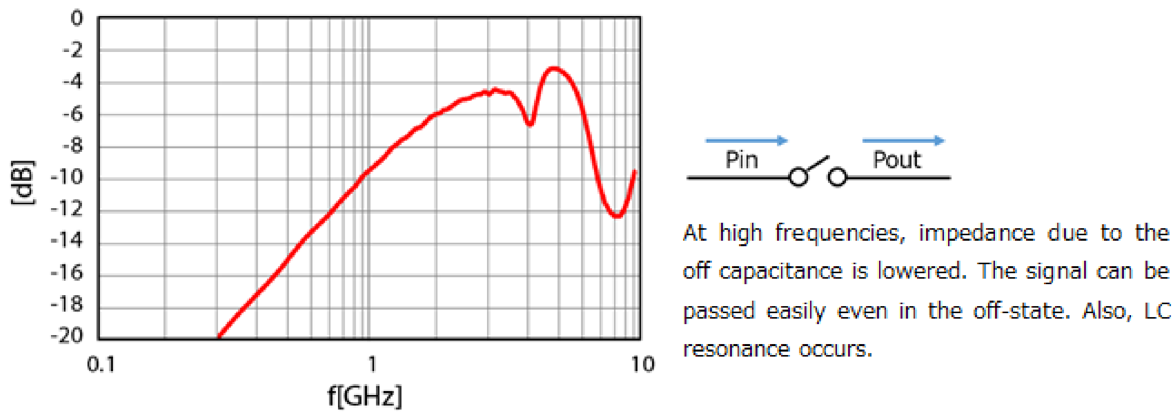


Fig. 8　Isolation characteristics

4.4 Return loss

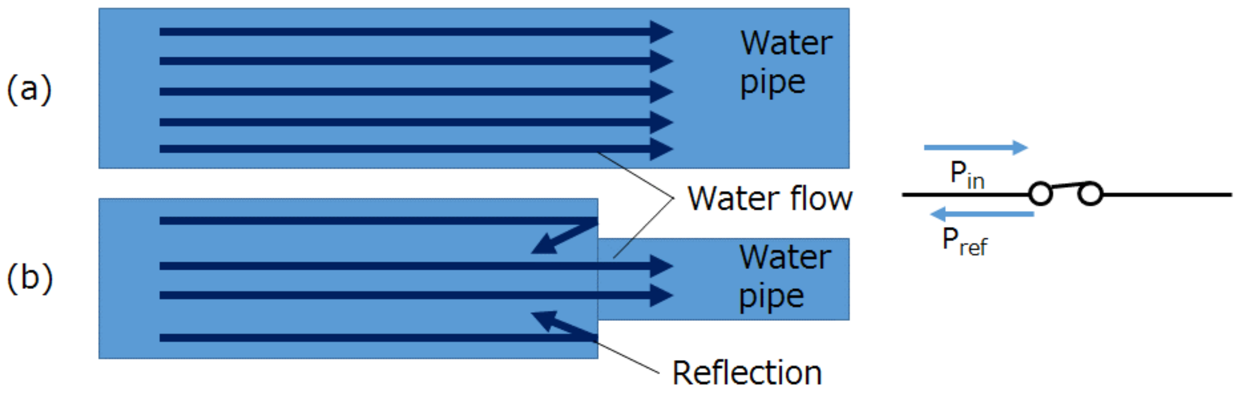
Impedance mismatches cause signal reflections.

This situation can be imagined as water flow in a pipe (Fig. 9). If the diameter or cross-section shape of the water pipe (impedance) changes at a point as shown in Fig. 9(b), the water (signals) will not flow smoothly and will be reflected partially. In addition, this is equivalent to a noise sourse because of the water flow turbulence.

The magnitude of the signal reflection is called return loss, which is expressed in dB (decibels) as the ratio of the input power P_{in} and the reflected power P_{ref}. The return loss is calculated by the formula below. The large negative value means low reflection. As the frequency increases, a large signal reflection occurs due to the impedance mismatch influence, thus the insertion loss increases.

$$\text{Return loss (dB)} = 10log_{10}\left(\frac{P_{ref}}{P_{in}}\right)$$

Examples) -10 dB: 1/10 (10 %) signal reflection   -20 dB: $1/10^2$ (1 %) signal reflection
-30 dB: $1/10^3$ (0.1 %) signal reflection -60 dB: $1/10^6$ (0.0001 %) signal reflection



(a) When the diameter or cross-section area of the water pipe is constant
= The signals flow smoothly when the impedance matches
(b) The diameter or cross-section area of the water pipe changes
= The reflection occurs at the impedance mismatched point

Fig. 9 Return loss (analogy from water flow in a pipe)

4.5 Phase

As the frequency increases, the parasitic reactance of the transmission line causes a phase difference between the voltage and current at the load as shown in Fig. 10. In the low frequency range, the phase difference is small because the value of the parasitic reactance is small. However, under high frequencies, the phase difference becomes large due to the influence of the parasitic reactance. The active power P describes as $P = VI\cos\theta$, where voltage is V, current is I, and the phase difference between the current and voltage is θ. When the phase difference is 90°, $\cos 90° = 0$, which means that the supplied power to the load is zero.

When selecting a component (photorelay) adopting to a high-frequency circuit, the insertion loss and the isolation performance of the photorelay itself should be important rather than the phase difference. Toshiba can offer phase data of photorelays. However, in actual circuit design, it is necessary to match the entire circuit phase including other external components from the perspective of the impedance matching for entire tranmission line.

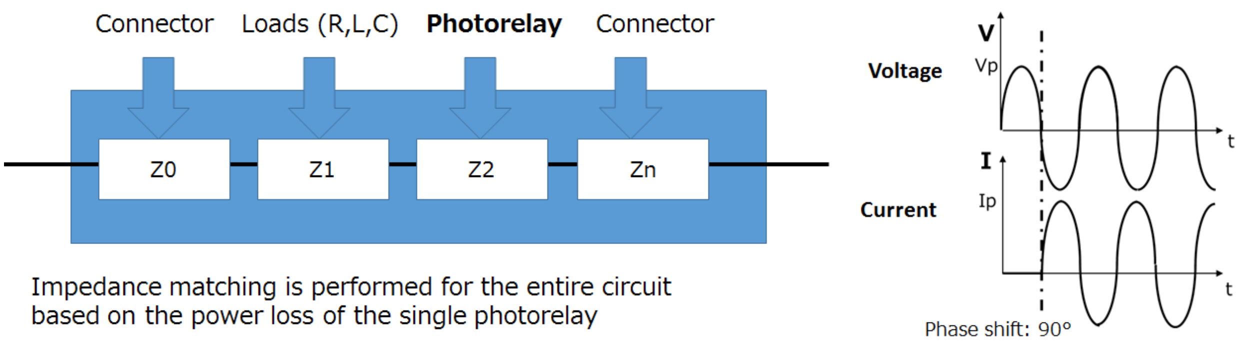


Fig. 10 Phase difference and impedance matching

5. S-prameter example

<S-parameter file format (s2p file)>

The s2p file is a data format used to load the measured S-parameter data into the circuit simulator. Table 2 shows an measured S-parameter numeric example after converting tablar format from the s2p file. S_{11} and S_{22} represent the return loss, and S_{12} and S_{21} represent th e insertion loss.

Table 2 S-parameter numeric example

frequency (Hz)	S11 (dB)	S11 phase (°)	S21 (dB)	S21 phase (°)	S12 (dB)	S12 phase (°)	S22 (dB)	S22 phase (°)
10000000	-38.81	2.11	-0.09	-0.19	-0.09	-0.20	-40.34	-11.38
34993750	-39.38	-16.31	-0.10	-0.64	-0.09	-0.64	-39.50	-9.87
59987500	-38.97	-22.27	-0.10	-1.08	-0.10	-1.08	-39.30	-22.62
84981250	-38.24	-30.25	-0.10	-1.52	-0.10	-1.51	-39.02	-27.91
109975000	-38.12	-37.51	-0.10	-1.96	-0.10	-1.95	-37.89	-35.18
134968750	-37.50	-42.12	-0.11	-2.42	-0.10	-2.41	-37.34	-43.70
159962500	-36.97	-51.15	-0.12	-2.85	-0.11	-2.85	-36.94	-48.80
184956250	-37.10	-57.27	-0.13	-3.28	-0.12	-3.28	-36.77	-57.37
209950000	-36.16	-55.13	-0.12	-3.64	-0.12	-3.63	-36.82	-57.21
234943750	-34.73	-62.05	-0.12	-4.11	-0.12	-4.10	-35.66	-61.88
259937500	-34.36	-64.47	-0.13	-4.57	-0.12	-4.56	-34.80	-66.71
284931250	-33.55	-69.62	-0.14	-5.04	-0.13	-5.04	-33.80	-70.15
309925000	-33.58	-77.99	-0.16	-5.46	-0.16	-5.45	-33.41	-77.13

6. Photorelay selection

The TLP3475S / TLP3440S is one of our products with good S_{21} (insertion loss and isolation performance).

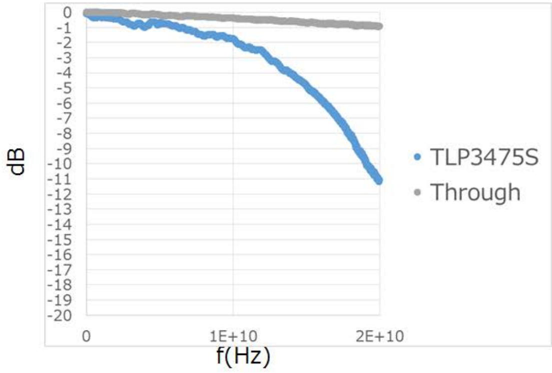
(1) The TLP3475S has a small R_{ON} (1.1 Ω (typ.)) and has reduced inductance components with an innovative packaging structure. It has excellent insertion loss characteristics.

(2) The TLP3440S has a small C_{OFF} (0.45 pF (typ.)) and excellent isolation performances.

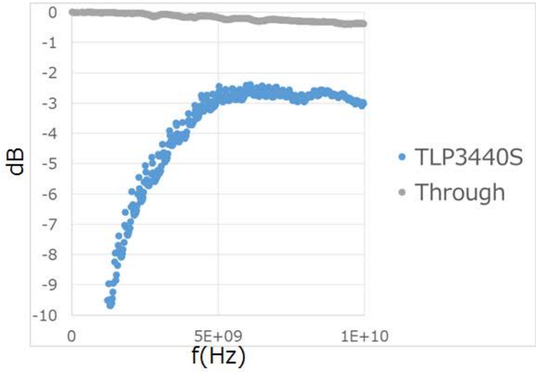
However, when handring signals of GHz order, if possible, it is recommended that a component with high impedance is connected to the photorelay output in series.

Fig. 11 shows insertion loss (isolation) characteristics (No de-embedding (*)).

*De-embedding: a post-measurement process to minimize errors from measurement system such as jig and substrate, and reveal data about the device under test



(a) TLP3475S insertion loss (LED: on)



(b) TLP3440S isolation (LED: off)

Fig. 11 Insertion loss and isolation characteristics

7 Photorelays suitable for high frequency signal control

In the end of the document, we introduce our photorelays suitable for high-frequency signal control. Selecting a low R_{ON}, low C_{OFF}, a low C×R photorelay (product of R_{ON} and C_{OFF}), and the small package are also advantageous in terms of lower impedances, making the product selection for high-frequency circuits. Generally, R_{ON} of about 1 Ω (typ.) and C_{OFF} of about 1 pF (typ.) are preferred for testers and measuring instrument applications.

Select from VSON4, S-VSON4, S-VSON4T package, which is the industry's smallest (Note) as a photorelay (Table 3).

(NOTE) As of September 2020, our survey

Table 3 Recommended products (as of September 2020)

Type	Contact	Package	VOFF (min.)	ION (max.)	IFT (max.)	RON (typ.)	RON (max.)	COFF (typ.)	IOFF (max.)	tON (max.)	tOFF (max.)	BVs(min.)
TLP3431	1-Form-A	VSON4	20V	450mA	3mA	**0.8Ω**	1.2Ω	5pF	1nA	0.5ms	0.5ms	500Vrms
TLP3475		VSON4	50V	300mA	3mA	**1Ω**	1.5Ω	12pF	1nA	0.5ms	0.4ms	500Vrms
TLP3450		VSON4	20V	200mA	3mA	**3Ω**	5Ω	**0.8pF**	1nA	0.2ms	0.2ms	500Vrms
TLP3442		VSON4	40V	100mA	3mA	15Ω	20Ω	**0.3pF**	1nA	0.2ms	0.2ms	500Vrms
TLP3440		VSON4	40V	120mA	3mA	12Ω	14Ω	**0.45pF**	1nA	0.2ms	0.3ms	500Vrms
TLP3441		VSON4	40V	140mA	3mA	5Ω	10Ω	**0.7pF**	1nA	0.2ms	0.2ms	500Vrms
TLP3451		VSON4	60V	120mA	3mA	10Ω	15Ω	**0.7pF**	1nA	0.2ms	0.2ms	500Vrms
TLP3406S		S-VSON4	30V	1500mA	3mA	**0.1Ω**	0.2Ω	120pF	1nA	2ms	1ms	500Vrms
TLP3475S		S-VSON4	60V	400mA	3mA	**1.1Ω**	1.5Ω	12pF	1nA	0.5ms	0.4ms	500Vrms
TLP3440S		S-VSON4T	40V	120mA	3mA	12Ω	14Ω	**0.45pF**	1nA	0.2ms	0.3ms	500Vrms

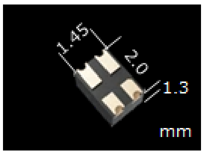


Fig. 12 S-VSON4T package

8 Conclusion

This document introduces considerations when using a photorelay to control high-frequency signals. We will continue to improve the performance and miniaturize photorelays and expand our lineup of our photorelays can handle signals in the higher frequency range. Please consider our photorelays for semiconductor testers and various measuring instruments.

When designing a new product, please check the latest product information on our website.

Revision history

Revision	Date	Page	Description
Rev. 1.0	2020-09-30	-	1st edition

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