# Complex impedance of optical transition-edge sensors with sub-microsecond response

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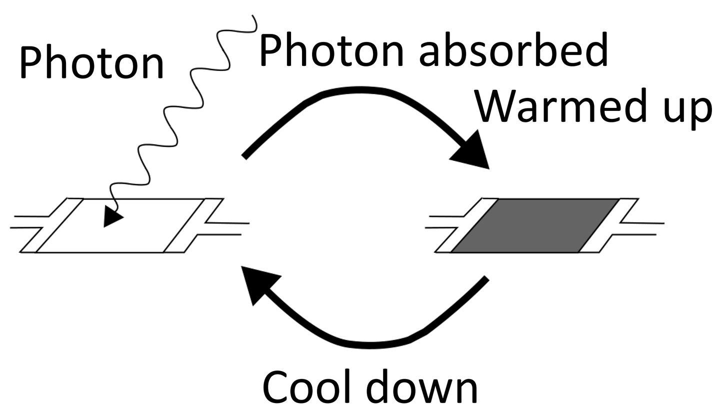
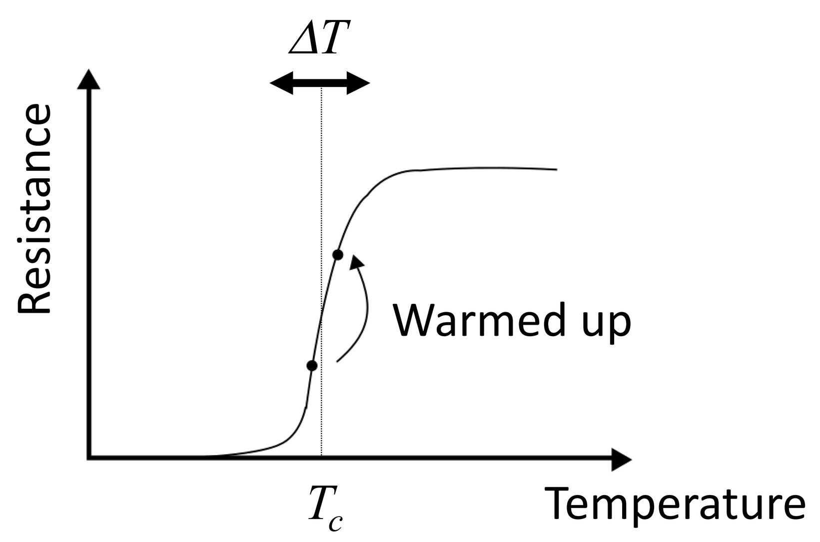
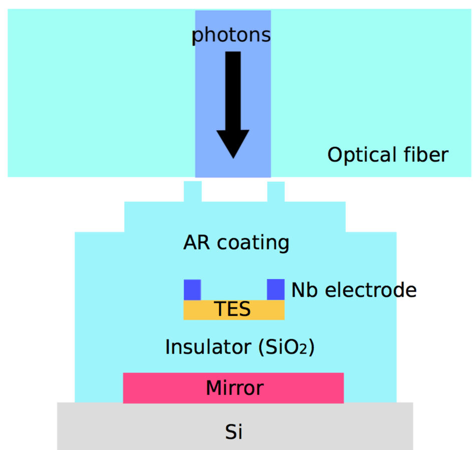
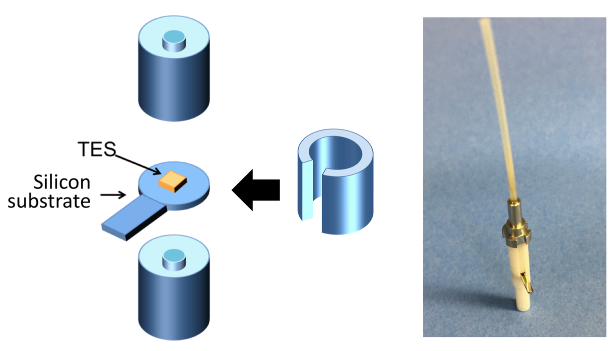
Optical transition edge sensor (TES) detectors that can resolve an energy of a single optical photon have proven desirable in multicolor fluorescence microscopy. In this application, detectors with higher energy resolution can distinguish dyes with closer emission wavelengths and enable us to observe more kinds of dyes simultaneously. To improve the energy resolution, we should know how far the measured energy resolution is from the limit determined by the temperature sensitivity α and current sensitivity β, extracted from the complex impedance. Due to very fast response of the optical TESs (τ < 1 μs), the complex impedances need to be measured above 10 MHz. At high frequencies, the parasitic impedance in the circuit and reflections of electrical signals due to discontinuities in the characteristic impedance of the readout circuits become significant. They limited the available bandwidth of the legacy readout. To reduce them, we have replaced the legacy twisted pair cables with coaxial ones and obtained cleaner transfer function of the readout at high frequencies. The measured impedance agreed with the single-block model at both high and low loop gains.

## Optical transition edge sensors



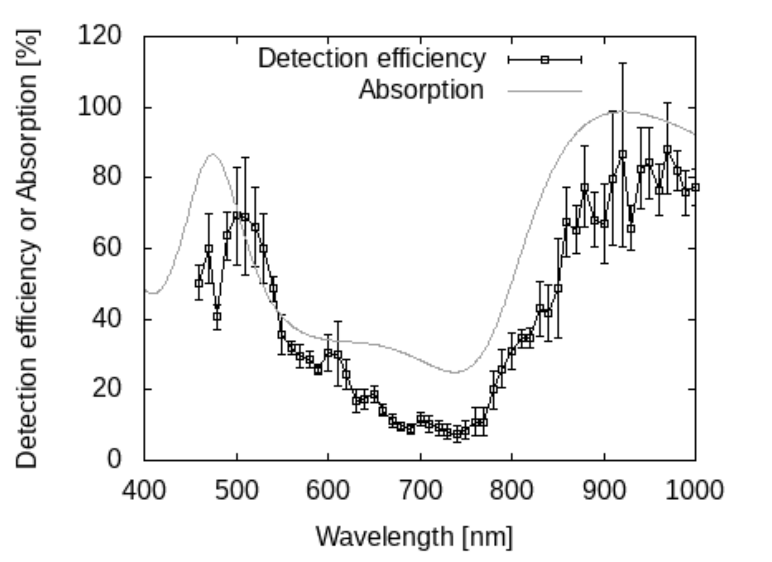

Self-aligning
A. J. Miller et al., Opt. Exp. vol. 19, 9102, 2011.

Optical transition edge sensors (TESs) are characterized by

- Thin layers : Ti (20 nm) / Au (10 nm)
- Small size : 5 to 10 µm  $T_c$ : 0.3 K
- Fast response time : $\tau$ ∼200 ns to a few µs
- High detection efficiency (nearly 100 %) at specific wavelengths
- Energy resolution : Typically 0.1 to 0.2 eV

TES is embedded in an optical cavity. Anti-reflection coating and a mirror are optimized to maximize absorption(nearly 100 %) at a desired wavelength.

System detection efficiency




K. Hattori et al., IEEE Trans. Instr. Meas. 68 2253 (2019).

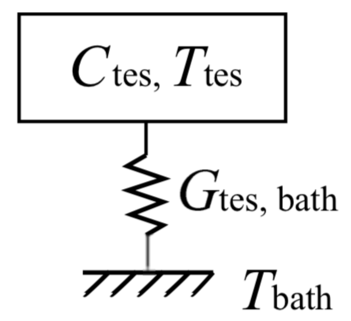
See also
Application : D. Fukuda, invited talk on 25 July
TES array : T. Konno, poster (75)
Microwave SQUID multiplexer : N. Nakada, poster (109)

The TES is also sensitive to photons at a wavelength apart from the targeted one.

Absorption was calculated using Essential Macleod.
https://www.thinfilmcenter.com/essential.php

## Complex impedance

Single-block model

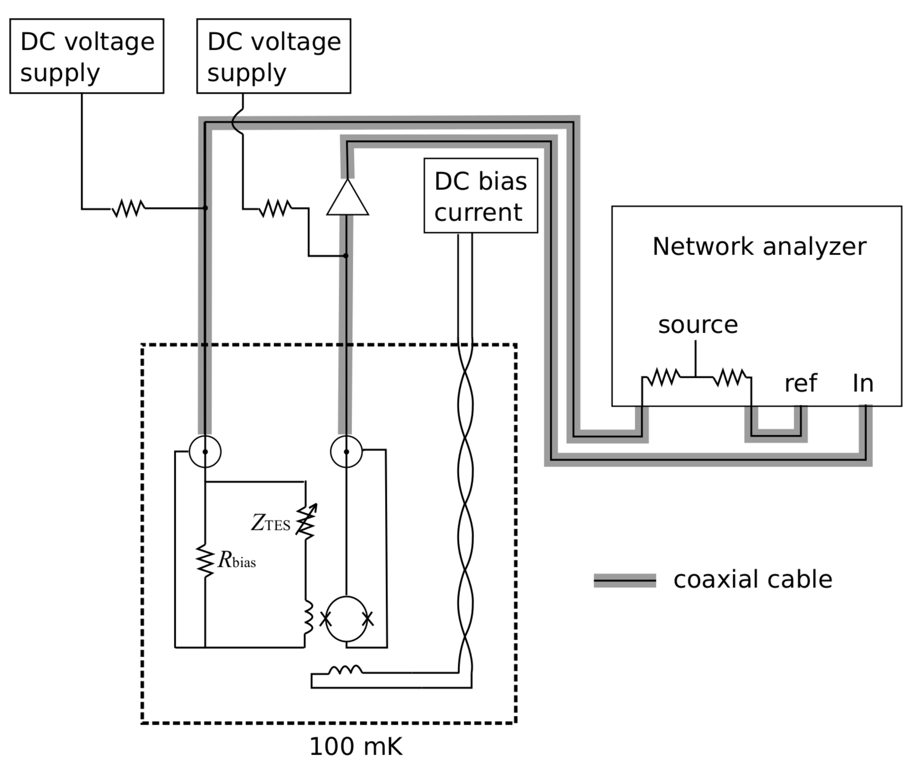


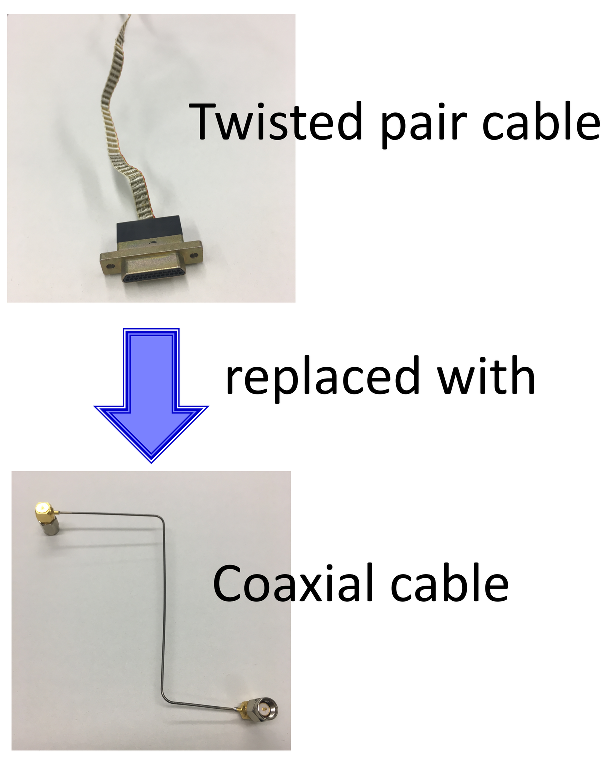

The single-block model explains behaviors of a TES that does not possess any absorber.

$$Z_{TES}(\omega) = R_0(1+\beta) + \frac{R_0\mathscr{L}}{1-\mathscr{L}}\frac{2+\beta}{1+i\omega\tau_I}$$

Complex impedance up to 1 MHz measured using the legacy readout [1].

Complex impedance at $f$ > 10 MHz needs to be measure to extract parameters. The current sensitivity $\beta$ is extracted from the high frequency limit of the complex impedance, $R_0(1+\beta)$.



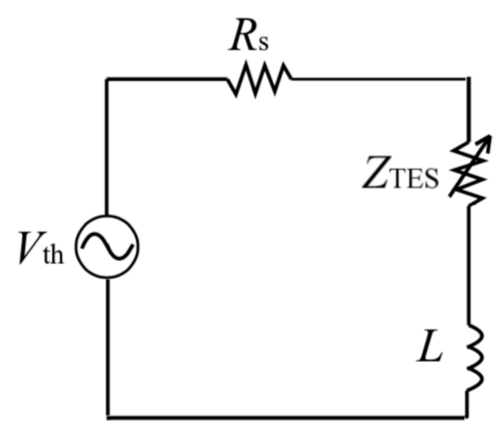




AC perturbations on the voltage bias and output SQUID signals are transferred through coaxial cables.

[1] E. Taralli et al., 2013 IEEE 14th International Superconductive Electronics Conference (ISEC) Page(s): 1-4

## Complex impedance measurement at high frequency

Thévenin equivalent circuit

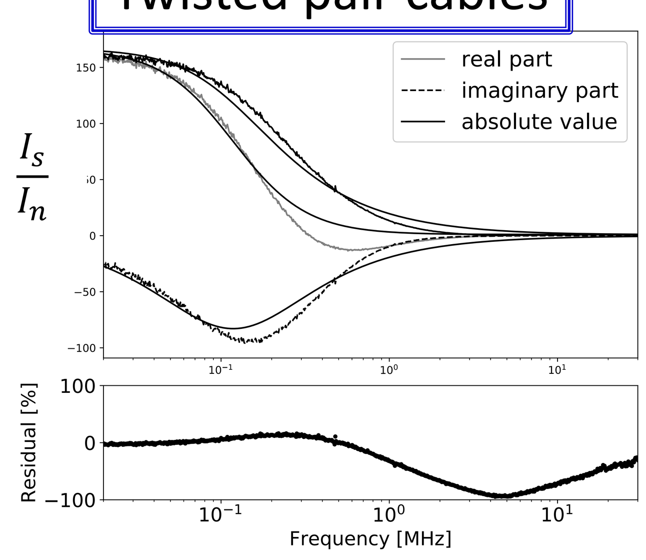



$$V_{th} = (Z_{tes} + R_s + i\omega L)I_{tes}$$

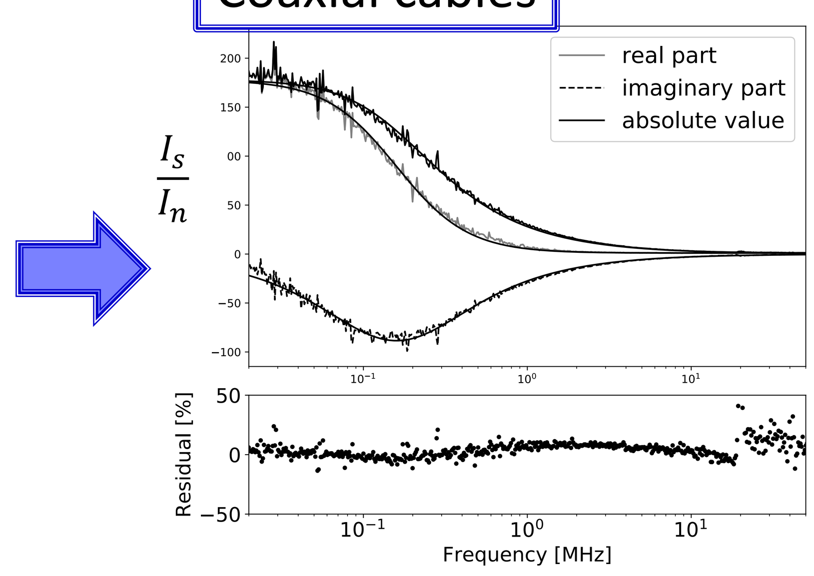
Take the ratio of current in the normal state ($I_n$) and the superconducting one ($I_s$) to vanish $V_{th}$.

$$\frac{I_s}{I_n} = \frac{R_n + R_s + i\omega L}{R_s + i\omega L}$$

Twisted pair cables

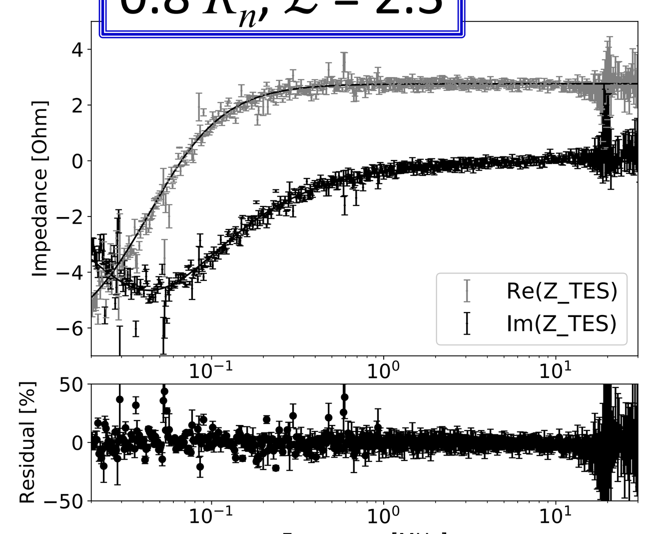



Coaxial cables

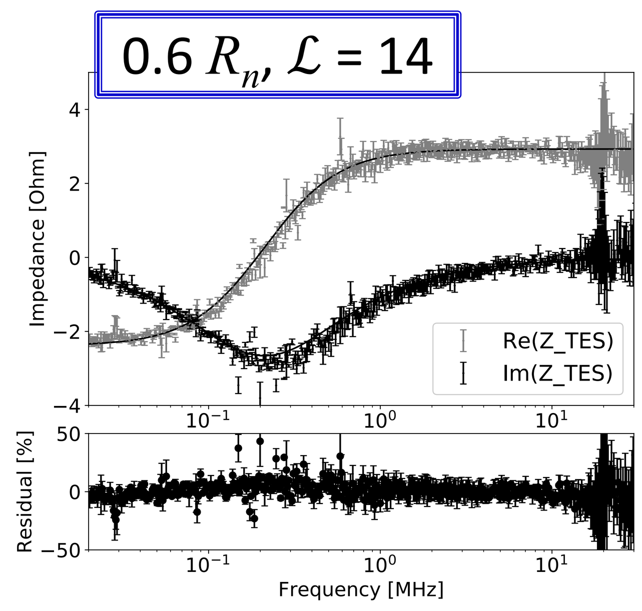



The new readout can be modelled as the simple Thévenin equivalent circuit at high frequencies.

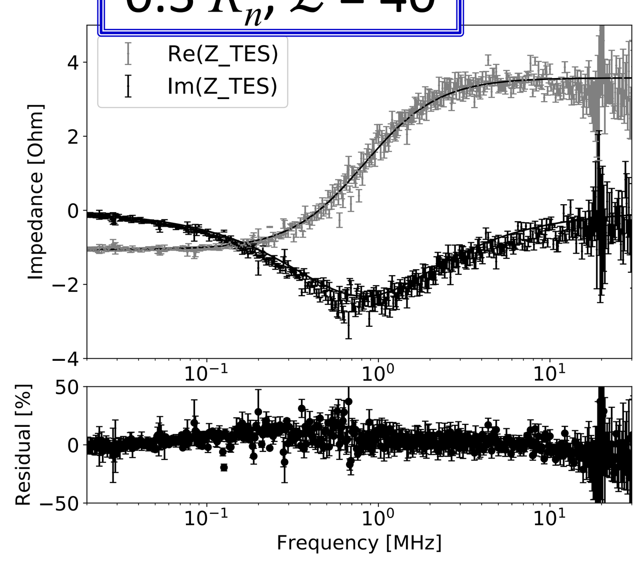
0.8 $R_n$, $\mathcal{L}$ = 2.3



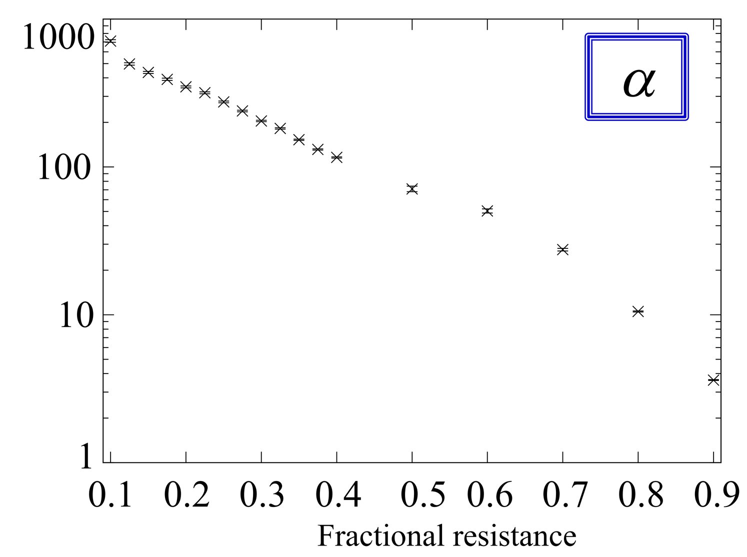

0.6 $R_n$, $\mathcal{L}$ = 14



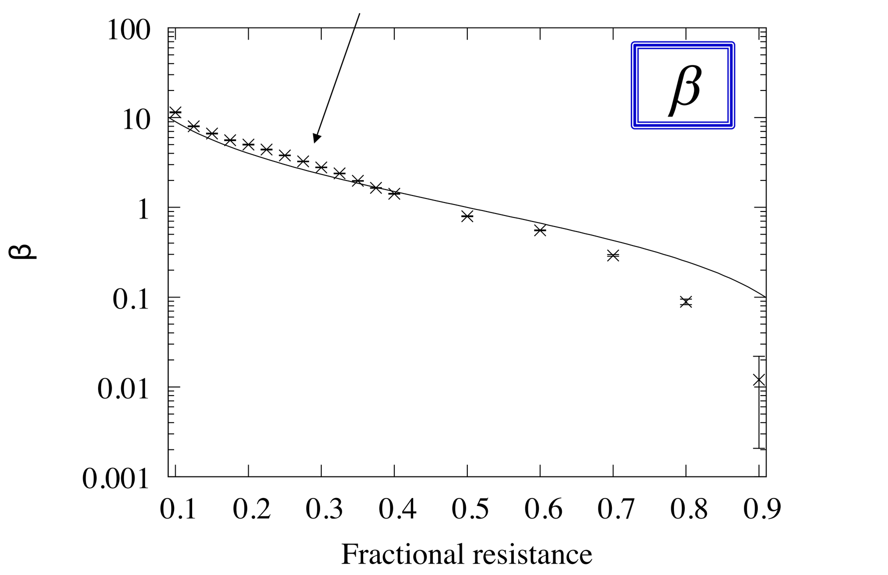

0.3 $R_n$, $\mathcal{L}$ = 40

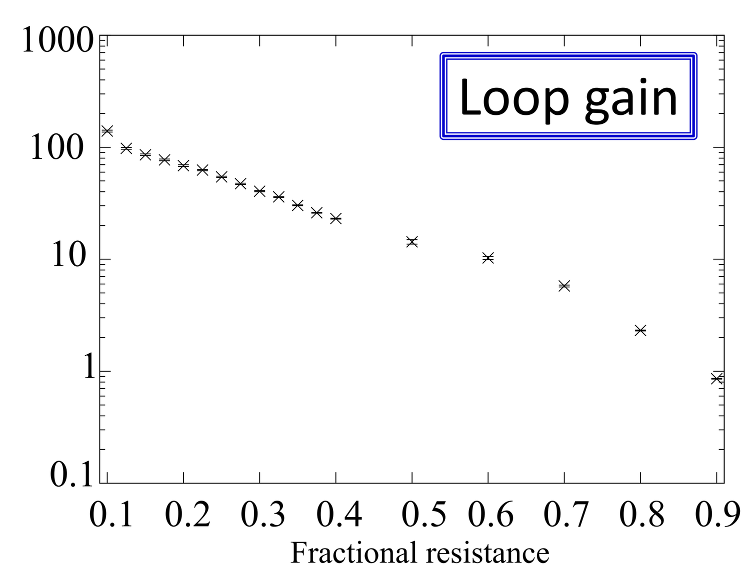



Coaxial cables were used.
The measured impedance agreed with the single-block model.




$\frac{R_n}{R_{tes}} - 1$ : upper limit on $\beta$ given by two-fluid model




Conclusion

- ✷ Tested a very fast TES detector with a time constant shorter than 1 µs.
- ✷ Coaxial cables offered a cleaner transfer function of readout for complex impedance measurements at high frequencies.
- ✷ Measured complex impedance agreed with the single-block model at both high and low loop gains.

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